ABSTRACT

Title of Dissertation: MODULUS BASED COMPACTION QUALITY ASSURANCE FOR UNBOUND MATERIALS USING LIGHTWEIGHT DEFLECTOMETER

Zahra Afsharikia, Doctor of Philosophy, 2019

Dissertation directed by: Professor Charles W Schwartz, Civil Engineering Department

Moving away from traditional density-based methods of compaction quality assurance (QA) towards modulus-based procedures using Light Weight Deflectometer (LWD) require developing practical framework to: (1) determine soil-specific LWD target modulus, and (2) evaluate LWD modulus in the field effectively. This dissertation draws upon work from two research studies, TPF-5(285) pooled fund study and pilot projects conducted by Maryland State Highway Administration to refine the two proposed QA specifications for road base, subgrade, and embankment construction. The practical method of establishing the target modulus based on LWD drops on compacted Proctor molds was proposed and evaluated. Three types of LWDs (Zorn ZFG3000, Olson LWD-01, Dynatest 3031) were utilized and their field to target modulus ratio was compared to the percent compaction as a criterion for goodness of compaction. Results confirmed the validity of procedures for the variety of geomaterials tested and suitability for practical implementation by field inspection personnel. Target modulus values, calibrated acceptance criteria, sampling method, and frequency is presented for future implementation in the state of Maryland and other state DOTs. The LWD manufacturers collaborated to facilitate the implementation by instrument design and improvement or software/application development.

# MODULUS BASED COMPACTION QUALITY ASSURANCE FOR UNBOUND GRANULAR MATERIAL

by

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Dissertation submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
2019

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# Dedication

To my loving parents, Sarah and Alireza.

To my best friend Matt.

Acknowledgements

Firstly, I would like to express my sincere gratitude to my advisor Professor Charles Schwartz for the continuous support of my study at University of Maryland, for his patience, motivation, and immense knowledge. His brilliant guidance helped me in all the stages of research and writing of this dissertation.

I am also grateful to my thesis committee, Professor M. Sherif Aggour, Professor Dimitrios Goulias, Professor Ahmet Aydilek, and Professor McClusky for their insightful comments and encouragement.

I am thankful to the Maryland, Virginia, North Carolina, South Carolina, Minnesota, Missouri, Indiana, Florida, and New York Departments of Transportations for their contribution to this research and participating in the Transportation Pooled Fund project TPF 5(825). Special gratitude goes to Dan Sajedi from the Maryland Department of Transportation State Highway Administration (MDOT SHA) for his devotion and leadership.

Sincere thanks to our LWD device providers, Virginia and Garry Aicken of Kessler Soils Engineering Inc. representative of Zorn Instruments, Larry Olson and Stan Smith of Olson Engineering, and Dr. Sadaf Khosravifar of Dynatest Consulting Inc.

I thank Infrastructure lab manager, Alfred Bituin, and my fellow lab mates Dr. Sadaf Khosravifar, Gregory Koepping, Ramiz Vatan, Marcus Lapa Watson, Mateus Coelho, Christopher Platt, and Nico Alvarez for their stimulating discussions and assistance during the field and lab testing. I am also thankful to Pam, Heather, and Christina from the CEE graduate office, for their kind support throughout my graduate studies. And finally, I am grateful for my friends, Matt and Samira, who helped me during this journey.

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# 1. Chapter 1: Introduction

The foundations of most roads and pavements are prepared by compacting unbound geomaterials in unsaturated conditions. Current density-based methods of compaction quality control (QC) and quality assurance (QA) requires achieving a certain percentage of maximum dry density (MDD) as determined from Proctor compaction tests in the laboratory (AASHTO T99 or T180), depending on the material type (subgrade, base, embankment, etc.) and layer's depth from the final grade.

Density-based methods of compaction QA using nuclear density gauges (NDG) has been the conventional practice for many years. Density is a relatively easy property to measure in the field, and it loosely correlates to more fundamental engineering properties. However, density is not a direct input to the structural design of the pavements and is not directly linked to pavement performance. Elastic modulus is the basic material input required for the structural design of pavements.

The particle arrangement in the soil structure may vary substantially without any significant change in the dry density (Hveem and Carmany, 1949), resulting in different soil behavior and properties. Ralph Proctor attempted to clarify misunderstandings of his proposed soil moisture-density relationship (Proctor, 1948). He mentioned that neither shear strength nor consolidation of compacted soils are proportional to the percentage of the MDD. For instance, "95% of standard MDD" does not necessarily secure 95% of a soil's shear strength. He in fact used a Penetration Needle to find the correct soil moisture content (MC) for compaction and the Indicated Saturation Penetration Resistance as a measure of compaction.

Modulus-based compaction QA of unbound materials is becoming popular as NDG testing becomes less appealing because of safety, regulatory, and cost concerns. In addition, the density-based QC/QA methods do not capture the stiffness changes over time in stabilized geomaterials.

The Lightweight Deflectometer (LWD) is a portable device that can be used to measure the in-situ modulus directly. LWDs are being employed for pavement construction QA in a few states and countries now, but their broader implementation has been hampered by the lack of a widely recognized standard for interpreting the measured stiffness data obtained.

There are extensive challenges in establishing such a standard specification, including the differences in the configurations of the various commercial LWD devices, the dependence of soil modulus on moisture and stress conditions, and the differences in the stress states and boundary conditions between typical laboratory tests and field conditions.

Despite these challenges, LWDs are promising tools for performance-based construction QA testing that will not only result in a better constructed product but will also provide the engineering properties critical for better understanding of the connection between pavement design and long-term pavement performance.

This dissertation draws upon work from two research studies: (1) Transportation Pooled Fund study TPF-05(285) "Standardizing Lightweight Deflectometer Modulus Measurements for Compaction Quality Assurance" and (2) an implementation pilot project by the MDOT SHA "Implementation of Lightweight Deflectometer for Modulus-Based Compaction Quality Assurance of Unbound Materials in the State of Maryland".

Initially three different LWDs were examined during the pooled fund study: The Zorn ZFG 3000 LWD, Dynatest 3031 LWD, and Olson's LWD-1 devices were selected as representing the range of commercially available configurations. Preliminary investigations were conducted in controlled large-scale experimental setting by Khosravifar (2015).

In addition to evaluation of the LWDs, a non-nuclear water content measurement technique was assessed for replacement of NDG measurement.

The concept of LWD testing directly on the compacted Proctor mold was developed to derive the target modulus values for the field. Field validation and supplementary lab testing were conducted for evaluating the proposed test equipment and LWD on Proctor mold methodology. Repeatability and reproducibility of the LWD measurements in actual construction practice was assessed.

The research findings were codified in two modulus-based QA draft specifications intended for practical implementation by state DOTs and engineers. The test protocols and data interpretation procedures are in AASHTO format. Both are reasonably easy to implement and do not increase field workload significantly. The spatial variability of moisture, density, and modulus was captured for the final refinement of a practical QA procedure.

## 1.1. Problem statement

The mechanistic-empirical pavement design method requires the elastic resilient modulus as the key input for characterizing geomaterials. Current density-based QA procedures using NDG do not measure resilient modulus. The high costs associated with the radiation-safe operation of NDGs also encouraged the search for an alternative.

In order to replace the conventional methods with a practical modulus-based specification using LWDs, several components are required:

(1) Fundamental understanding of LWD configurations and data interpretation.

(2) A target modulus value to aim for after compaction.

(3) A testing method and data analysis procedure that does not increase field workload significantly, so that the agencies will be able to adopt and implement easily.
(4) Consideration of the LWD devices' variabilities and the effects of moisture/drying, stress states/levels, and finite layer thickness on measured stiffness.
(5) Emphasis on the importance of moisture content control at the time of compaction.
(6) Recommendations for field compaction, sampling, and control.

## 1.2. Objectives

The principal objective of this research is to provide a straightforward procedure for using LWDs for modulus-based compaction QA that is suitable for practical implementation by field inspection personnel. To meet this objective, the following work elements were defined and pursued:

(1) Literature review of existing applications of LWDs for modulus-based QA.
(2) Preliminary evaluation of LWD load and deflection measurements.
(3) Assessment of the effects of LWD device details—e.g., plate diameter, plate rigidity, contact area stress distribution, loading rate, and deflection measurement locations.
(4) Formulation and validation of a target modulus determination method using LWD.
(5) Evaluation of field moisture content measurement alternatives to NDG.
(6) Verification of the proposed LWD modulus-based QA approach under actual field conditions.
(7) Drafting of practical LWD modulus-based QA specifications in AASHTO format.

The secondary objectives of the study include: (1) determining the minimum required LWD testing and data collection in the field based on the typical standard deviation of field modulus values for compaction QA; (2) establishing appropriate acceptance criteria and lower specification limits for a percent-within-limits QA approach; and (3) reporting typical target moduli for unbound materials for future use in design.

## 1.3. Literature review

Lessons learned from two project reports NCHRP 10-84 (Nazarian et al, 2014) and NCHRP Synthesis 20-05/Topic 44-10 (Nazzal, 2014) served as the main resources for the literature review.

Early work by Fleming et al. (2000), Vennapusa and White (2009), Senseney et al. (2009, 2012, and 2014), and Stamp and Mooney (2013) showed the potential of LWDs for determining the moduli of compacted soil layers. A few of these studies along with the recent NCHRP Synthesis 382 (Puppala, 2009) noted the need for more research to evaluate the ability of LWDs to determine the moduli of prototype test sections and also to address the effects of stress dependency and layering on the moduli measurements.

The ASTM Standard *Test Method for Measuring Deflections with a Light Weight Deflectometer* (ASTM E2583-07) and *Measuring Deflections using a Portable Impulse Plate Load Test Device* (ASTM E2835-11) only provide standards for measuring deflections using an LWD. They do not provide a standardized way to interpret those deflection measurements for the calculation of stiffness or modulus.

There are several studies in the literature on stress dependency and moisture dependency of the stiffness of geomaterials (example: Nazarian et al., 2014, Gupta et al., 2007, Carry and Zapata, 2010). However, the effect of dry density is found rather unpredictable and material dependent. This, in one hand makes it reasonable to move forward to modulus-based QC/QA of geomaterials but in the other hand challenging it. In NCHRP Project 10-84, Nazarian et al. (2013) tried to capture the effect of compaction MC, testing MC, and density on modulus. Free-free resonant column (FFRC) tests showed that the greater the difference between the MC at compaction and testing, the higher will be the seismic modulus which in turn is correlated with resilient modulus (Mr). They also found that the effect of density was negligible as compared to MC.

The LWD has been extensively assessed in several European countries (Fleming et al., 2007) and a number of state DOTs in the United States including Virginia, Indiana, Minnesota, Florida, Nebraska, and Montana (Hossain & Apeagyei, 2010; Mooney & Miller, 2009; Nazzal et al., 2007). A variety of target modulus determination methods were used, including control strip construction, correlation with field DCP or sand cone measurements, and laboratory resilient modulus testing (Glagola et al., 2015; Siekmeier et al., 2009; Nazzal, 2014; Nazarian et al., 2014).

The target modulus/deflections that are typically derived by Mr testing (AASHTO T307) are difficult to adjust for field moisture conditions. This led to the new approach developed here of using LWD testing directly on the Proctor compaction mold to find the target field modulus at a given moisture condition. This test is an easy add-on to the routine Proctor test and can be used to determine the target LWD modulus in field. It also provides valuable insights into the soil's response to moisture, density and stresses that can be used to tailor the compaction criteria in field.

## 1.4. Organization of this dissertation

The main body of this dissertation is organized to summarize the principal findings that have been integrated in the proposed specifications. Supporting details are provided in appendices as appropriate.

The first chapter presents an introduction to the study, its objectives, and a summary of the state of practice for modulus-based QA of unbound material using LWD.

Chapter 2 describes of the methodology employed, including equipment selection, LWD testing in the field and modulus calculation, laboratory testing plan, and LWD on mold methodology and modulus calculation.

Chapter 3 provides a summary of the test sites visited and material characteristics.

Chapter 4 presents the results of the field validation program and testing methodology as described in Chapter 2. The significant findings include: evaluation of selected MC measurement equipment, a summary of LWD and NDG measurements in the field, results of LWD on mold testing, comparisons of field to modulus ratio criteria versus PC. Further details on the results of the field and laboratory testing are presented in the Appendices.

Chapter 5 presents the acceptance criteria determination and sampling frequency calculation for implementation of LWD for compaction QA. The draft versions of the two specifications for lab and field LWD testing are developed in this chapter. These are subsequently refined in Chapter 6 to reflect lessons learned during field validation.

Chapter 6 presents the testing program and results of the MDOT SHA's pilot study. Also described are the procedure to match the LWD loading pressure in the laboratory to the field, an experiment to find a correction factor for the effects of oversized particles on target modulus, repeatability of LWD on mold testing, several observations on the Proctor testing method, and an investigation into the effect of LWD plate size and deflection measurement location (top of the soil versus top of the plate) in the field. Chapter 6 also include the specifications and recommendations for the MDOT SHA compaction QA procedure. Target LWD moduli are calculated for the common aggregate sources evaluated in this study. Acceptance criteria are determined and described, and minimum testing frequencies are suggested. Final refinements to the specifications are also described in this chapter.

Chapter 7 summarizes the principal findings and conclusions from the study and provides recommendations for future research.

Appendix A provides the implementation-ready draft specifications in AASHTO format and QA recommendations.

Appendix B includes all the field testing details for the pooled fund study.

Appendix C provides tabulated summary of LWD, MC, and NDG measurements in the field.

Appendix D presents the details and results of LWD testing in the field and implemented QA procedure for the test sites in the state of Maryland.

# 2. Chapter 2: Methodology

This chapter presents the equipment evaluation and selection process, field testing procedure, data collection and calculation, and lab testing methods that were developed during the pooled fund study TPF-5(285). Available devices for in-situ modulus, density, and moisture content measurement were reviewed. The evaluation of in situ modulus measurement devices focused on commercially available LWD models including the Zorn ZFG 3.0, Dynatest 3031 LWD, and a prototype of the new LWD-01 by Olson Engineering.

Assumptions made for lab and field testing as well as LWD modulus calculation during the pooled fund study are included in this chapter.

## 2.1. Equipment

Factors considered in the LWD device selection were load levels, load buffer system, plate diameter, deflection sensor type, data acquisition system, precision and accuracy, ease of use, and experience of other users.

Available moisture measurement techniques suitable for field use were evaluated with regard to speed in obtaining results, data acquisition, accuracy, and practicality.

### 2.1.1. ***Lightweight Deflectometer (LWD)***

The Lightweight Deflectometer (LWD) or Light Falling Weight Deflectometer (LFWD) is a portable dynamic plate loading test developed to measure in-situ deflection under applied load and calculate the modulus ($E_{LWD}$) of geomaterials.

Figure 1 presents a typical LWD device configuration. The sliding drop weight acts as a loading mechanism which, depending on the required applied pressure, can be changed from 2 kg (4.4 lbs) to 20 kg (44 lbs). A 10 kg (22 lbs) drop weight is often used for unbound material testing in the field. The drop weight is locked and secured using a release handle which can be fixed (to keep a constant drop height/applied load) or movable to allow for different drop heights.

Once released, the weight freely slides on the vertical rod and exerts a haversine shaped load pulse through the buffer system to the loading plate. The buffers can be rubber or steel, cone shaped or cylindrical, and may be adjustable to achieve different pressures and load pulse durations. The plate is a steel or aluminum disk, typically available at 100 mm (4 in.), 150 mm (6 in.), 200 mm (8 in.), and 300 mm (12 in.) diameters. The loading plate may be solid or contain an annular hole at the center. The Dynatest LWD is an example of a device having an adjustable damping system that is capable of exerting 50 kPa (7.25 psi) to 150 kPa (21.75 psi) pressure on a 300 mm plate with a 10 kg to 20 kg drop weight.

The loading plate is assumed to be in full contact with the underlying unbound material layer and to move together with the layer in a coupled mode under the applied load. The drop weight then bounces back and is caught by the operator.

The speed or acceleration of the plate's vertical movement is captured using a velocity transducer (geophone) or accelerometer, depending on the device type and location of the sensor. Then the speed/acceleration is integrated/double integrated to calculate the deflection of the LWD plate on the underlying layer. Some LWD brands offer two or three external geophones to measure the velocity at different radial distances from the center of the plate.

The applied load history is measured via a load cell in some device types (e.g., Dynatest LWD, Olson LWD, Prima LWD, Terratest LWD) or the peak load is calibrated for a fixed drop height and drop weight (ex. Zorn LWD, Humboldt LWD).

The measurements are collected in a data acquisition device such as a logger, personal digital assistant (PDA)/handheld PC, mobile phone (with IOS or Android operating system), or tablet linked via wire or Bluetooth connection. Most LWD brands have recently added a GPS module to automatically capture the testing location's coordinates. The accuracy of the GPS measurements varies with the device and sophistication of the technology.

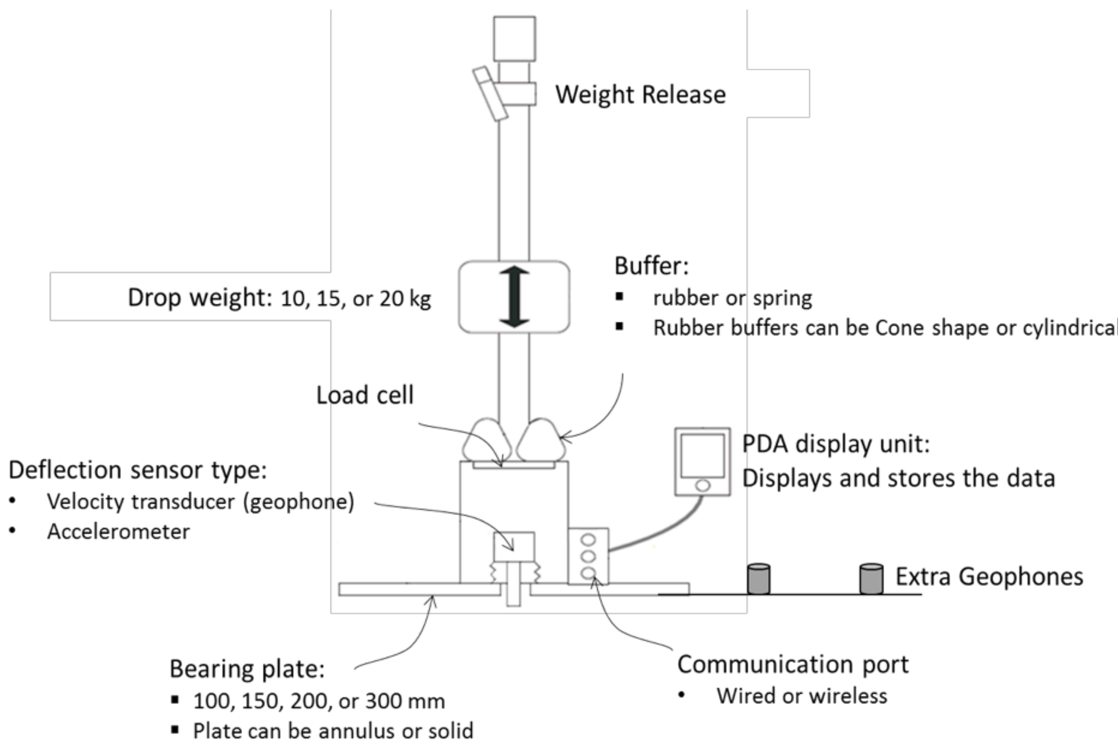



**Figure 1. A typical LWD instrument configuration (from Khosravifar, 2015)**

The configuration and characteristics of a variety of LWDs were investigated during the literature review in the pooled fund study (Schwartz et al., 2017). These are summarized in Table 1. A few of the devices were developed for research purposes only. Among the commercially available LWDs at the time, three representative devices were selected to span the range of device characteristics: the Zorn ZGF 3000 series with the data logger and printer system (Figure

2, a), Dynatest 3031 with handheld wireless PDA (Figure 3), and Olson LWD-01 with NDE 360$^{TM}$ data collection platform (

Figure 4, a). The LWD manufacturers implemented multiple refinements of their LWDs over time as a result of this study and similar implementation projects.

Table 2 presents a summary of the selected LWD devices' configuration. The Dynatest and Olson LWDs have load cells and geophones that measure the load and deflection histories during every drop. The Zorn LWD calibrates their configuration for a peak force of 7.07 kN (1.59 lbs) at a standardized drop height and assumes a constant force for all soil types irrespective of their stiffness. The Zorn LWD captures data in sets of six drops using an accelerometer: the first three drops are seating drops and deflections are displayed on the data logger, the last three drops are measurement drops which is reported as the layer's deflections.

The Zorn and Olson LWD each have a solid plate with the acceleration sensor mounted on top of the plate at the center. The Dynatest unit measures the velocity directly on top of the ground via a rod through the central annular hole in the plate. The Dynatest LWD also has the option to plug the annular hole to measure velocity on top of the plate (Figure 3, b). The dual plate system in the Dynatest unit allows rapid changes between the 300 mm and 150 mm plate sizes.

There are two ASTM standards available for measuring deflections with an LWD device: ASTM E2835 and ASTM E2583. The standards specify apparatus requirements, calibration of load and deflection sensors, signal conditioning and recorder system, LWD testing procedure, and required precision and bias. The Dynatest LWD conforms to ASTM E2583 with deflection sensor precision of ±2 μm (0.08 mils) and load cell precision of ±0.1 kN (22 lb). The Zorn and

Olson LWDs conform to ASTM E2835 with deflection precision of ±40 μm (1.6 mils).

**Table 1. Characteristics of various LWDs (After Vennapusa and White 2009, Nazarian et. al 2009, Mooney and Miller 2009)**

| Device | Plate Style | Plate Diameter (mm) | Plate Thickness (mm) | Falling Height (cm) | Falling Weight (kg) | Plate Mass (kg) | Maximum Applied Force (kN) | Load Cell | Total Load Pulse (ms) | Type of Buffers | Deflection Transducer: Type | Deflection Transducer: Location | Deflection Transducer: Measuring Range (mm) | Data Acquisition system | Additional/ external Deflectometer |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Zorn ZFG2000, Germany | Solid | 100, 150, 200, 300 | 124, 45, 28, 20 | 72 | 10, 15 | 15 | 7.07 | No | 18±2 | Steel Spring | Acceler-ometer | Plate | 0.2-30 (±0.02) | SD card for data transfer to PC<br>Deflection and final modulus portable printer<br>Reading deflection and dynamic modulus on the display | - |
| Keros PFWD, Dynatest, Denmark | | 150, 200, 300 | 20 | | 10, 15, 20 | | 15 | Yes | 15-30 | Rubber (Conical shape) | Velocity | Ground | 0-2.2 (±0.002) | - | |
| Dynatest 3031 | Annulus | 100, 150, 200, 300 | 20 | | 10, 15, 20 | | 15 | Yes | 15-30 | Rubber (Flat) | Geophone | Ground | 0-2.2 (±0.002) | Handheld PDA with a wireless Bluetooth connection<br>The data collection software on the PDA displays the surface modulus and the time history graph from both the geophone(s) and the load cell | Two additional external geophones (optional) |
| Prima 100, Carl Bro Pavement Consultants, Denmark | Annulus | 100, 200, 300 | 20 | Max 85 Variable | 10, 20 | 12 | 15 | Yes | 15-30 | Rubber (Conical shape) | Velocity | Ground | 0-2.2 (±0.002) | A portable PC or a PDA with a data collection program installed<br>Reading data on the display | Extension with a beam for two extra geophones is possible |
| Loadman, AL-Engineering Finland | Solid | 110, 130, 200, 300 | - | 80 | 10 | 6 | 20 | Yes | 25-30 | Rubber | Acceler-ometer | Plate | - | - | |
| ELE | | 300 | - | | 10 | | | No | | | Velocity | Plate | - | - | |
| CSM, Colorado School of Mines | Solid | 200, 300 | - | Variable | 10 | 6.8, 8.3 | 8.8 | Yes | 15-20 | Urethane | Geophone | Plate | - | - | |
| Olson | Solid | 100, 150, 200, 300 | Different thickness for each plate diameter | Max 60 Variable | 2, 9 | Variable | 9 | Yes | 20 | Spring | Geophone | Plate | | Handheld ruggedized Dell tablet with cable connection<br>The data collection software on the tablet displays the surface deflection and the time history graph from both the geophone(s) and the load cell | Two additional external geophones (optional) |
| Humboldt | Solid | 300 | 20 | - | 10 | - | 7.07 | No | 17±1.5 | Disk | Acceler-ometer | Plate | 0.1-2 (±0.02) | A handlheld controller with cable connection<br>Portable thermal printer and USB<br>PC software and Android app | |

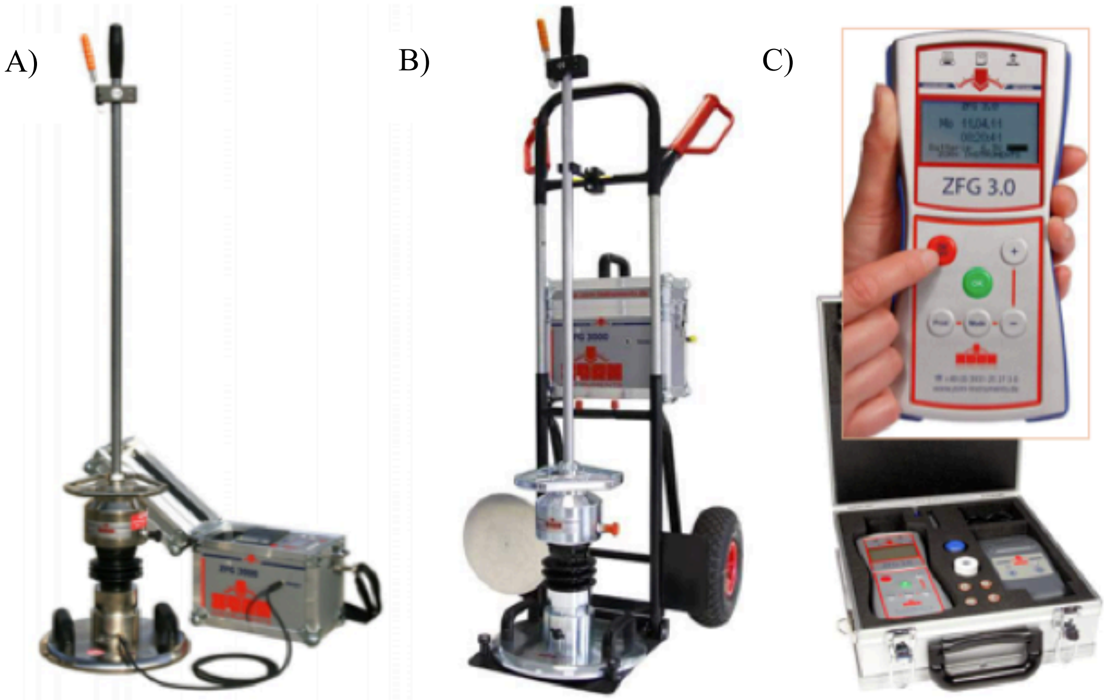



**Figure 2. Zorn LWD: (A) ZFG 3000 series with the data logger and printer system in one unit, (B) Zorn transport trolley, and (C) ZFG 3.0 handheld data logger with separate printer (pictures courtesy of Zorn Instruments)**

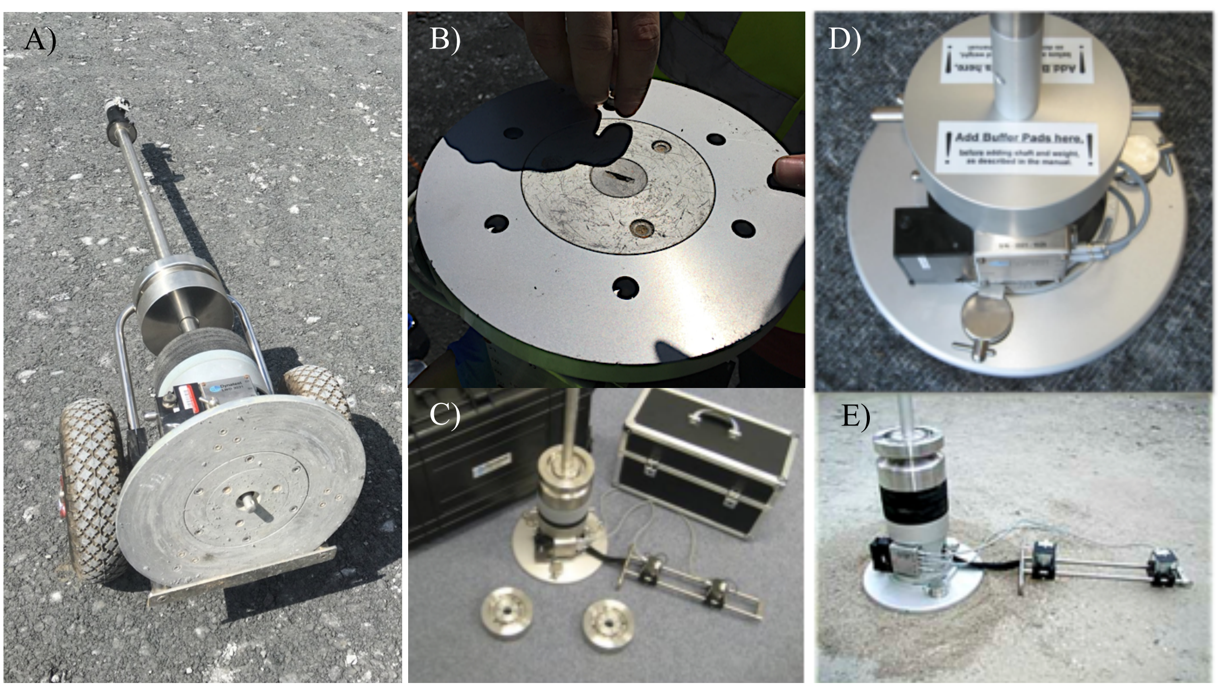



**Figure 3. Dynatest LWD 3031: (A) annular plate and deflection rod, (B) plug for annular hole, (C) extra 5 kg weights added for higher applied force, (D) dual plare system, (E) LWD set up with the optional external geophones (pictures C,D, and E courtesy of Dynatest International)**

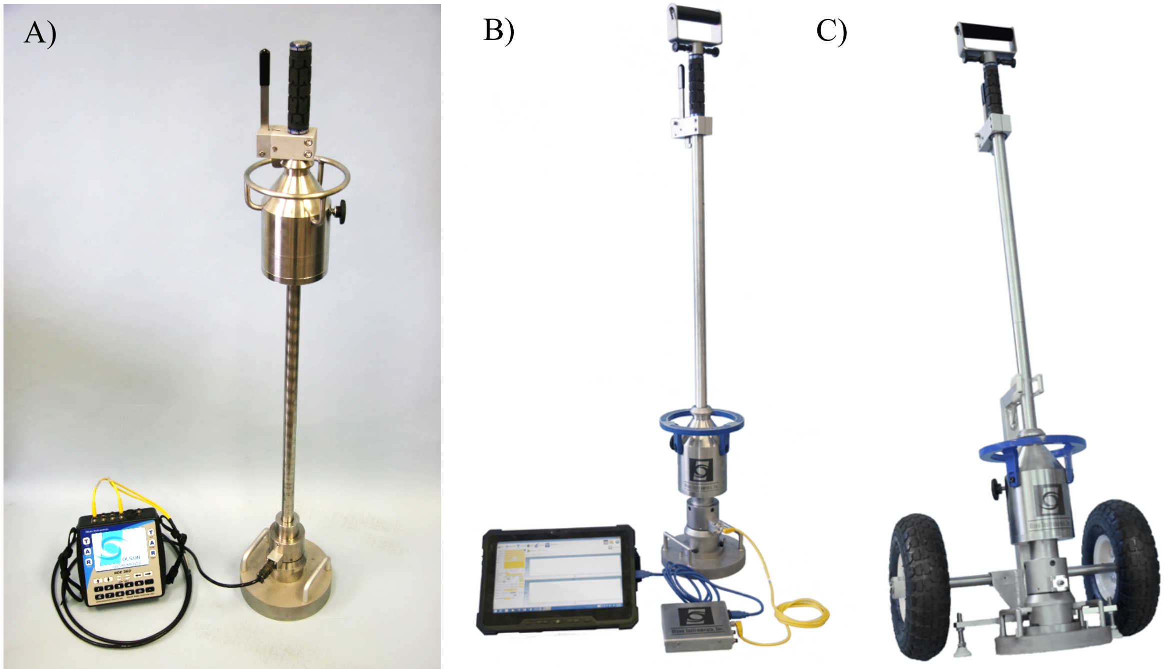



**Figure 4. Olson LWD: (A) LWD with NDE 360™ data collection platform (B) LWD-01with the new ruggedized DELL tablet, and (C) transport cart (pictures courtesy of Olson Instruments Inc.)**

**Table 2. LWD devices configuration**

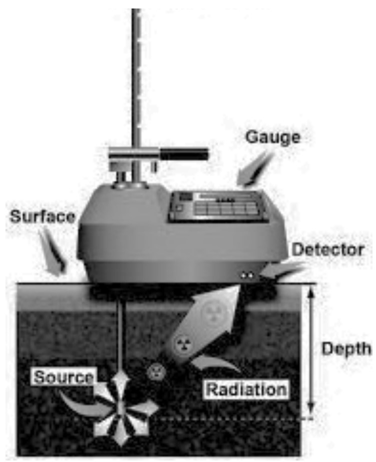
| | | unit | LWD: Zorn ZFG3000 | LWD: Dynatest 3031 | LWD: Olson 01 |
|---|---|---|---|---|---|
| **Total device weight (10 kg weight) and for plate diameters** | 100 mm | [kg] | 30.1 | 19.8 | 27.1 |
| | 150 mm | [kg] | 30.2 | 20.1 | 24.8 |
| | 200 mm | [kg] | 30.4 | 20.5 | 26.7 |
| | 300 mm | [kg] | 30.2 | 23.3 | 26 |
| **Drop weight** | | [kg] | 10, 5 | 5, 10, 15, 20 | 3.6, 5, 10 |
| **Maximum drop height** | | [cm] | 72.4 | 83.8 adjustable | 60 adjustable |
| **Load cell available** | | [-] | No | Yes | Yes |
| **Deformation sensor** | **type** | [-] | Accelerometer | Geophone +2 optional external geophones | Geophone |
| | **range** | [mm] | 0.2–30 (±0.02) | 0–2.2 (±0.002) | N/A |
| **Plate type** | | [-] | Solid | Annulus | Solid |
| **Type of buffer** | | [-] | Spring | Flat Rubber-adjustable | Spring |

### 2.1.2. ***Nuclear Density Gauge (NDG)***

Nuclear Density Gauges (NDG) have been in use for in-situ measurement of MC and density of soils, asphalt, and concrete for over thirty years. NDG consists of a radiation source that emits a directed beam of particles that are either reflected or passed through the test material and a sensor that counts the received particles. Two different radioactive sources are used to produce two different types of radiation in NDGs: (1) Cesium 137 that releases gamma ray photon radiation for density determination, and (2) Americium 241 (combined with non-radioactive Beryllium), which emits neutron radiation to determine moisture content. The particle count is a function of hydrogen content of the material and to a lesser degree, affected by other low atomic number elements such as oxygen and carbon (Christopher et al., 2013). By calculating the percentage of returned particles to the sensor, the gauge can be calibrated to measure the density of the test material. ASTM provides standards for calibration facility setup for NDGs (ASTM D7013) and for NDG calibration (ASTM D7759).

NDGs can be used in two modes as exhibited in Figure 5: (1) direct transmission for soils and unbound material testing. First, a drill rod is driven into the ground with a hammer to make an access hole. Then the NDG source rod is lowered in the hole to a suitable depth depending on the constructed layer thickness (up to 300 mm). (2) Backscatter transmission that is commonly used for asphalt tests or very stiff stabilized and compacted soil. No access hole is driven for a backscatter mode. The source rod is locked in the base of the NDG at the top of the testing surface. The gamma ray photons penetrate the material to a maximum depth of 75 to 100 mm (3–4 inches) and reflect back to the detectors at the other side of the gauge. Direct transmission is more accurate than backscatter transmission but takes longer to perform.

Annual radiation safety training and monitoring is required for all technicians working or transporting the gauges. NDG testing and data collection in this study was performed by state DOT certified operators using a Troxler 3440 nuclear moisture-density gauge in direct transmission mode according to ASTM D6938 (Figure 6). NDG measurements along with LWD testing were performed at the same spot in the field to assess the spatial variability of PC, MC, and $E_{LWD}$ throughout the construction.

A) 

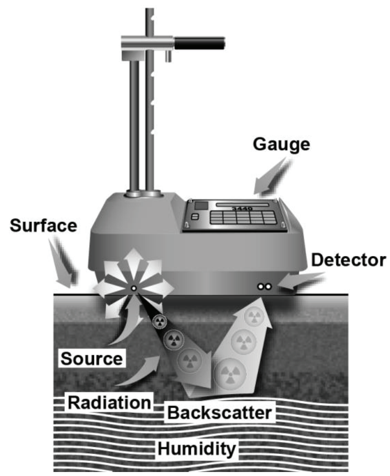
B) 


**Figure 5. Nuclear gauge in (A) direct transmission, and (B) backscatter transmission (from Iowa DOT's radiation safety and nuclear gauge training manual)**

A) 
B) 

**Figure 6. Troxler 3440 nuclear moisture-density gauge testing on compacted GAB in the field: (A) driving the hole for direct transmission mode, and (B) collecting the MC and density data after the test**

### 2.1.3. *MC measurement device*

The moduli values of geomaterials are highly affected by the compaction MC and post-compaction testing MC (Afsharikia, 2017). An appropriate rapid method of MC measurements must be included in field compaction QA procedures. The compaction water content should be measured during placement and before compaction to ensure it falls within the acceptable specification range. MC testing should also be performed concurrent with LWD modulus measurement after compaction.

The NDG is the most commonly used for MC as well as density measurement. However, several studies in the literature have investigated a variety of non-nuclear MC measuring devices and techniques (Sebesta et al., 2012, and Berney et al., 2011).

Christopher et al. (2013) constructed test pads with Coal Combustion Products (CCP) and evaluated a range of MC measurement devices and methods including: oven drying (ASTM D2216), NDG (ASTM D6938), push probes (Lincoln Soil Moisture Meter, General GLMM200 Moisture Meter, Kelway Moisture Meter, Decagon GS3 Moisture Probe, Hanna Instruments Soil Moisture Probe), and two vessels that measure pressure with calcium carbide (Speedy 2000 Moisture Device, DMM600 Duff Moisture Meter). A high variability in measured field MC was observed that was partly due to lack of adequate moisture control during placement.

Nazarian et al. (2014) also provides a comprehensive review of moisture/density devices as part of the NCHRP 10-84 study. As summarized in (Table 3), these included: Soil Density Gauge (SDG), Speedy Moisture Tester (SMT), Electrical Density Gauge (EDG), Moisture+Density Indicator (M+DI) device, and Road-Bed water content meter (DOT 600). This study assigned 86% of the total variation in measurements to the repeatability (or lack thereof) of the devices.

NCHRP 10-84 concluded that the device biases increase with an increase in the water content and/or plasticity in soils. The SMT was determined as the most accurate device and the DOT 600 the least.

**Table 3. Advantages and disadvantages of moisture/density devices. From Table 2.5.1– NCHRP 10-84 final report (Nazarian et al, 2014)**

| Device | Description | Advantages | Disadvantages |
|---|---|---|---|
| **Electrical Density Gauge (EDG)** | EDG uses a radio signal between four spikes to measure capacitance, resistance, and impedance of the soil. These parameters are used to determine the density and water content of an unbound layer. | Does not require a licensed technician. Repeatable. | The necessity to run a series of laboratory and in situ tests for correlation purposes. Poor success rate in identifying areas with anomalies |
| **Moisture + Density Indicator (M+DI)** | <u>*M+DI*</u> utilizes time domain reflectometry (TDR) to measure voltage time histories of an electromagnetic step pulse at four soil spikes in the ground. The voltage time histories are analyzed to determine the water content and density of an unbound layer. | Requires no certified operators, safety training, or instrument calibration. | Prior calibration of the device for each specific soil using laboratory compaction molds is required.<br>May not be appropriate for aggregates or earth-rock mixtures that either interfere with penetration of the probes or have numerous and large void spaces.<br>Time required to conduct a test may be of concern. |
| **Soil Density Gauge (SDG)** | SDG produces a radio-frequency electromagnetic field using a transmitter and receiver to estimate the in-place density, and moisture content of unbound pavement materials using electrical impedance spectroscopy (EIS). | Requires no certified operators, safety training, or instrument calibration. | The technology is new and limited research has been performed using this device. |
| **Speedy Moisture Tester (SMT)** | SMT measures the moisture content of geomaterial by measuring the rise in gas pressure within an airtight vessel containing a mix of soil sample and a calcium carbide reagent. | Portable and requires no external power source. Can measure many materials over a wide moisture content range. | Not suitable for all geomaterials, especially highly plastic clay soils. The reagent used is considered as a hazardous product. Compacted geomaterials have to be excavated before they can be tested. |
| **Road-Bed Water Content Meter (DOT 600)** | DOT600 estimates the volumetric water content of soil samples by measuring the dielectric permittivity of the material. | Sample bulk density and compaction force are monitored.<br>The system is completely portable. | The technology is new and limited research has been performed using this device. Prior calibration of the device for each specific soil is needed. Compacted geomaterials have to be excavated before they can be tested. |

Sotelo et al. (2014) compared three different MC measurement devices including SDG, SMT, and Time Domain Reflectometer (TDR). All devices demonstrated acceptable levels of repeatability. However, moisture contents measured by TDR and SMT during field evaluations were more comparable to those from the oven-dry method. The SMT tended to underestimate the moisture content, but this can be corrected through a calibration based on the oven-dry moisture measurements. The TDR and SMT exhibited less variability for different soil types as compared to the SDG. However, thorough calibration may enhance the SDG device performance, since it was found to be soil dependent. Nazarian et al. (2013) also confirmed that the SDG results were significantly lower than the oven-dried moisture contents by a factor of 2 based on tests on an embankment. However, in a later report from the NCHRP 10-84 project, Nazarian et al. (2014) states that the SDG is the least material dependent device.

Decagon ruggedized GS-1 volumetric water content measurements were evaluated against NDG measurements for the test pit soils during the TPF-5(285) study (Khosravifar, 2015, and Schwartz et al., 2017). It was difficult to insert the sensor when the soil was compacted to a high density. The sensor was also impractical for base aggregates with large nominal maximum aggregate sizes. A drill can be used to prefabricate holes when using the sensor on stiff fine-grained soils such as silty sand and high plasticity clay. Despite the difficulties with the sensor insertion and its unsuitability on base aggregate, there was acceptable agreement between the Decagon and NDG measurements. The Decagon sensor slightly underestimated the volumetric water content by about 10% on average.

Due to the moisture sensitivity of LWD deflection and modulus measurements, a practical non-nuclear method of gravimetric water content measurement (GWC) is needed. The Ohaus MB45 moisture analyzer (Figure 7) quickly determines the GWC like a portable mini-oven. The test procedure is straight forward. The soil sample is continuously heated by a halogen lamp while being weighed by an integral scale until the weight stabilizes. The Ohaus test takes about 10-15 minutes for aggregates and up to 30 minutes for fine grained soils depending on their MC.

Tefa (2015) preliminary compared Ohaus MB45 results to oven drying tests at various MCs in the laboratory using four different soil types: gravel, sand, silty sand, and clayey sand. A high correlation coefficient of 0.98 was observed between the Ohaus and oven drying MC measurements. Ohaus slightly underestimated the water content, which could be due to a shorter drying period and smaller sample size (45 gr only). A correction factor of 1.11 eliminated the underestimation. Khosravifar (2015) observed good correlations between the MC measured by the Ohaus MB45 and NDG for the test pit soils after applying the 1.11 correction factor.

Ohaus MB45 moisture analyzer was selected as a suitable method for further field validation. The limiting factors for this device include: (1) the low sample capacity, specially for larger aggregates, (2) a need for a stable surface away from wind and precipitation, and (3) a generator to power it in the field. The Ohaus can be safely positioned and leveled in the trunk of a car and powered using a Honda generator as shown in Figure 7. The inspector can alternatively use it in the field office if close by. On average, five MC samples could be tested during about 2 hours of inspection and LWD testing.

Recently, the new models MB90 and MB120 of the Ohaus moisture analyzer became available with higher sample capacities (90 gr and 120 gr respectively). More information regarding the Ohaus devices can be found at [Ohaus.com](Ohaus.com).

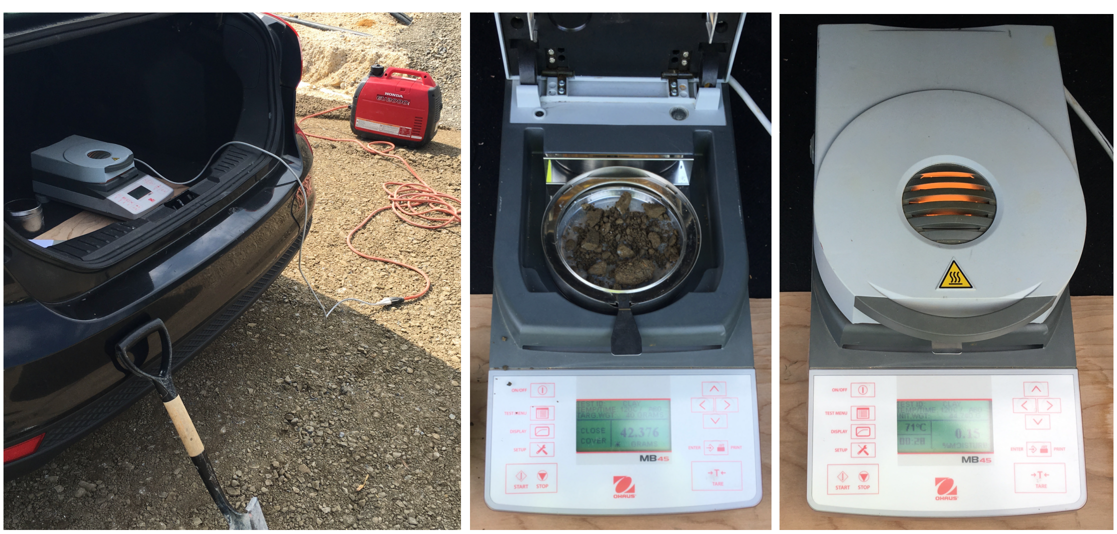


**Figure 7. Ohaus MB45 moisture analyzer testing a sample in the field**

## 2.2. Field testing plan

A field test and data collection plan was designed for verification of the proposed test equipment and methodology. The objectives included: (1) assessment of the practicality and repeatability of the test devices under actual construction conditions, (2) estimation of the spatial variability of MC, density, and modulus using the proposed devices and methods, and (3) development of a practical QA procedure.

Based on the outcome of test pit trials (Khosravifar, 2015), the field data collection plan specified the following tasks:

- Bulk sampling of subgrade, embankment, and/or base materials for laboratory determination of gradation, plasticity, soil classification, and Proctor moisture-density relationship.
- Recording the weather history, soil surface temperature, and noteworthy details during the construction and testing period.
- Measuring the in-situ compaction MC using the Ohaus moisture analyzer.
- Measuring the in-situ density and MC of the subgrade and/or base material at 1.5 m (5 ft) to 3 m (10 ft) intervals using NDG to quantify the spatial variability.
- LWD testing at 1.5 m (5 ft) to 3 m (10 ft) intervals in a grid as shown in Figure 8 to quantify the spatial variability.
- Field MC measurement was accompanied by sampling from the same LWD/NDG testing spot for subsequent oven moisture determination in the lab.

The test sites were selected based on the available construction projects at each participating state DOT and in consultation with the Technical Advisory Committee of the TPF-5(285) pooled fund study. The selected projects were intended to span a range of subgrade and base materials with various gradations, plasticity indexes, and moisture characteristics. Geological information for each site was provided by the respective agency. Details of the investigation program were tailored to the specific conditions at each site. Appendix B provides details of the selected projects and remarks.

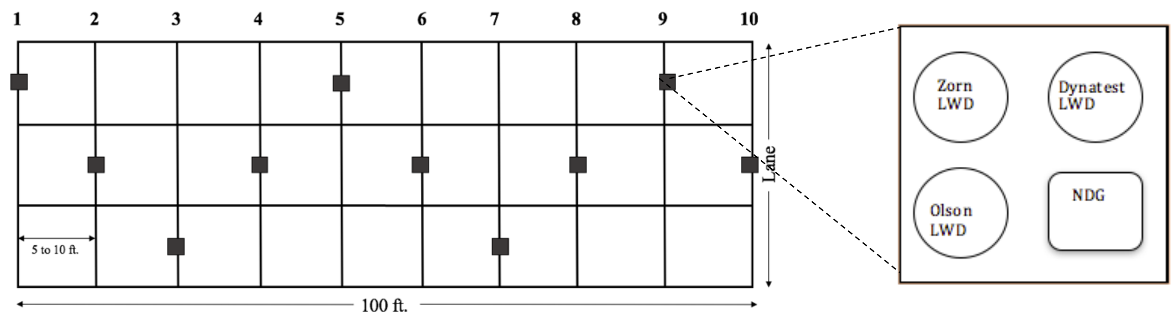



**Figure 8. Test locations along a compacted lane (left) and at each specific station (right)**

Test sites ranged between 15 m to 60 m (50-200 ft) long. Layers of geomaterial with about 15-30 cm (~6-12 in.) thickness were placed and compacted using vibratory drum rollers. To test the whole area of the test strip, the compacted layer was divided into 3 sub-lanes as shown in Figure 8, and LWD drops were performed on random locations in the sub-lane at 1.5-3 m (5-10 ft) apart and 0.3 m (1 ft) away from the edge of the road to avoid any boundary effects. LWD plates were placed at adjacent spots to avoid overlapping and possible extra compaction induced by consecutive LWD drops.

Six LWD drops were performed at each test location per device using the 300 mm (12 in.) diameter loading plate. The first three were treated as seating drops, and the second three were measurement drops used for $E_{LWD}$ calculation. The LWD applied load and/or deflections were monitored to confirm a haversine shape load pulse with a duration between 20 and 40 msecs according to ASTM E2583 for Dynatest and Olson LWDs and between 10 and 30 msecs for the

Zorn LWD according to ASTM E2835.

When the LWD's zone of influence was deeper than the compacted layer's thickness and the underlying layer had a significantly different modulus (ex. GAB compacted on soft subgrade), LWD testing was performed on the underlying layer at approximately the same locations as top layer prior to placement.

In some scenarios, the drop heights were varied between half height to full height, six drops from each height (total of eighteen drops), to evaluate the stress dependency of the moduli in the field.

Percent compaction measured using the NDG was used as a reference for the quality of compaction and for subsequent comparison to the field to target modulus ratio. The NDG testing was performed by certified operators supplied by the state DOTs and was concurrent to the LWD testing (keeping at a 6 m distance for safety). The measurements were performed in direct transmission mode at a depth approximately equal to the compacted layer's depth (Figure 9).

Furthermore, soil samples were extracted from the compacted layer at all test locations for MC measurement via oven drying in the lab according to AASHTO T265.

**Figure 9. LWD and NDG testing on the subgrade and base after compaction**

The testing timeline and the quantity of collected data are provided in the Appendix C.

The weather conditions for wind speed, air temperature, humidity and evaporation rate were recorded using a Kestrel weather tracker during the testing at each site. Additionally, the soil surface temperature was measured using a Fluke infrared thermometer at various random locations (Figure 10).


**Figure 10. Fluke Infrared Thermometer (left) and Kestrel 4300 Construction Weather Tracker (right)**

### 2.2.1. *Calculation of LWD modulus in the field*

Assuming the compacted layer to be a linear elastic, isotropic, homogeneous, and semi-infinite continuum, the Boussinesq formula was used to calculate the LWD modulus ($E_{field}$) from the peak load (F) and peak deflection (d) under the centerline of the applied load:

**Equation 1**

$$E_{field} = \frac{2k_s(1-\upsilon^2)}{Ar_0}$$

in which

$k_s$ = stiffness calculated by dividing the average measured F to the average d of the last 3 drops= $(F_4+F_5+F_6)/(d_4+d_5+d_6)$

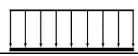
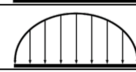
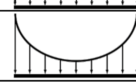
A = stress distribution factor

$\upsilon$ = Poisson's ratio

$r_0$ = plate radius

The stress distribution under the load plate depends on both load plate rigidity and material type, and therefore can be parabolic, inverse parabolic, or uniform (Table 4). The A factor was assumed to be equal to $\pi$ for the Zorn and Olson LWD, and $3\pi/4$ for Dynatest LWD. Poisson's ratio was assumed equal to 0.35 for all soil types in this section. Unless mentioned otherwise, the plate radius equaled 50 mm (6 in.) for all field testing.

**Table 4. Stress distribution factor (A) for different types of soil**

| **Soil type** | **Factor (A)** | **Stress distribution Shape** |
| --- | --- | --- |
| Uniform (mixed soil) | $\pi$ |  |
| Granular material (parabolic) | $3\pi/4$ |  |
| Cohesive (inverse-parabolic) | 4 |  |

## 2.3. Laboratory testing

The ability to predict resilient modulus of the soil at different moisture and density conditions was evaluated for nine resilient modulus constitutive models and empirical predictive models on several cohesive and noncohesive soils by Khosravifar et. al (2015). The results indicated that none of the existing models is precise enough to be used as the basis for target modulus determination.

This led to a new approach of using LWD testing directly on the Proctor compaction mold to find the target modulus at a given moisture condition. This test is an easy add-on to the routine Proctor test. It also provides valuable insights into the soil's response to moisture, density and stress that can be used to tailor the compaction criteria in field.

The laboratory efforts were designed to validate the LWD on mold approach with the objective of finding the target modulus at the given field moisture and stress state. Then the target moduli were compared to the field surface moduli by calculating the $E_{field}/E_{target}$ ratios.

During the field testing, two 5 gallon buckets of soil material were obtained from the subgrade and/or base material at each test site. Routine laboratory soil characterization tests were then performed on this sampled material. These tests included sieve analysis for gradation (AASHTO T27-11), Atterberg limits (AASHTO T89-13, and T90-00), and specific gravity (AASHTO T85-10, T84-10, and ASTM D854-14).

An appropriate quantity of about 7 kg (~15 lb) was separated from the sampled soil for compaction according to AASHTO T248. In order to keep the material gradation in the mold similar to the actual field gradation, only particles retained on the 25.4 mm (1in.) sieve were scalped. These oversized particles generally constituted less than 10% of the material by weight.

After comprehensive investigation, a 152.4 mm (6 in.)-diameter Proctor mold was deemed suitable for stable LWD testing. Molds were compacted at three to six different MCs according to AASHTO T 99 method B or D starting from approximately 4 percentage points below the expected OMC until observing a constant dry density or decrease in values (Proctor curve reached).

The compacted molds were stabilized and secured to the laboratory's concrete floor to avoid lateral movement. The LWD's loading plate was then placed on the compacted soil in the mold with the edges of the plate just clearing the rim (Figure 11). A simple collar was designed and attached to the mold after trimming the compacted surface to help keep the LWD loading plate in place (Figure 12).

The field testing exerted an average LWD pressure (applied force divided by the area of 300 mm loading plate) between 90 to 98 kPa (13 to 14.5 psi). To ensure that the $E_{target}$ from LWD using a smaller 150 mm plate is calculated at the same pressure as that in the field, LWD tests from lower drop heights were performed. The target moduli were then interpolated/extrapolated to the corresponding field plate pressure.

A)  B)  C) 

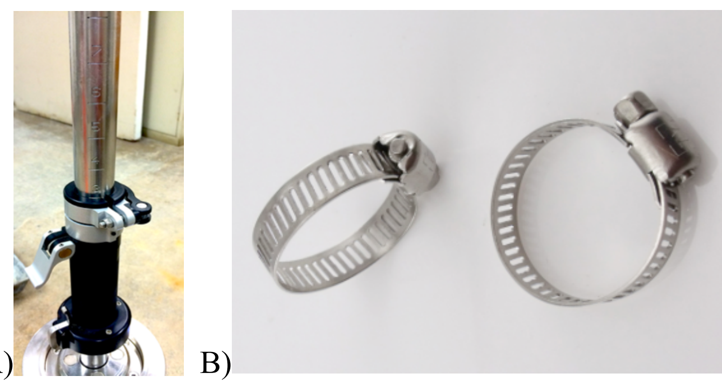
**Figure 11. LWD testing on Proctor mold for (A) Zorn, (B) Olson, and (C) Dynatest devices.**

**Figure 12. Collars used during LWD on mold testing**

Similar to the field testing, six drops from each drop height (total of thirty six drops) were performed on the mold starting from the lower drop height, then gradually increasing to higher ones. Drop heights for each LWD are listed in Table 5, which were precisely marked on the guide rods for the Zorn and Olson LWDs before testing. An adjustable pipe clamp was also used to ensure the drop weight is raised to the specified drop heights. The Dynatest LWD has a movable release handle and a laser engraved scale on the guide shaft for easy setting of the desired drop height (Figure 13). The testing order for the LWD devices was varied to avoid causing any systematic bias in the results.

**Table 5. Drop heights for LWD testing on molds**

| LWD type | Unit | height 1 | height 2 | height 3 | height 4 | height 5 | height 6 |
|---|---|---|---|---|---|---|---|
| **Zorn** | [cm] | 2.5 | 5.1 | 7.6 | 10.2 | 12.7 | 31.8 |
| **Dynatest** | [cm] | 2.5 | 5.1 | 7.6 | 10.2 | 12.7 | 17.8 |
| **Olson** | [cm] | 2.5 | 5.1 | 7.6 | 10.2 | 12.7 | 21.6 |



A) B)

**Figure 13. (A) Dynatest LWD's movable release handle and laser engraved scale on the guide shaft, and (B) adjustable pipe clamps to set lower drop heights for Zorn LWD**

### 2.3.1. ***Derivation of the LWD modulus on mold formula***

For an isotropically elastic material, the stress-strain relationships for the axially symmetric conditions in the Proctor mold under LWD loading are as follows:

**Equation 2**

$$\varepsilon_z = \frac{1}{E}(\sigma_z - 2\nu\sigma_h)$$

**Equation 3**

$$\varepsilon_h = \frac{1}{E}(-v\sigma_z + (1-v)\sigma_h)$$

in which:

$\sigma_z$ , $\varepsilon_z$ = axial stress and strain

$\sigma_h$ , $\varepsilon_h$ = radial stress and strain

For the case of one-dimensional strain where the stain in radial directions is zero:

**Equation 4**

$$\varepsilon_h = \frac{1}{E}(-v\sigma_z + (1-v)\sigma_h) = 0$$

**Equation 5**

$$\rightarrow \sigma_h = \frac{v}{1-v}\sigma_z$$

Replacing $\sigma_h$ in the $\varepsilon_z$ equation:

**Equation 6**

$$\varepsilon_z = \frac{1}{E}\left(\sigma_z - 2v\frac{v}{1-v}\sigma_z\right) = \frac{\sigma_z}{E}\ (1 - \frac{2v^2}{1-v})$$

Assuming the deflection occurs in the geomaterial only and not in the underlying stiff concrete foundation (Figure 14):

$$\varepsilon_z = \frac{\text{deflection}}{\text{lenght}} = \frac{d}{H}$$

$$\sigma_z = \frac{\text{force}}{\text{area}} = \frac{F}{\frac{\pi D^2}{4}}$$

$v$ = Poisson’s ratio

H = height of the mold

F = applied load (from LWD)

d = deflection on top of the soil (from LWD)

The constrained modulus of elasticity can then be calculated as:

**Equation 7**

$$E_{Mold} = \left(1 - \frac{2\nu^2}{1-\nu}\right)\frac{4H}{\pi D^2} \times \frac{F}{d}$$

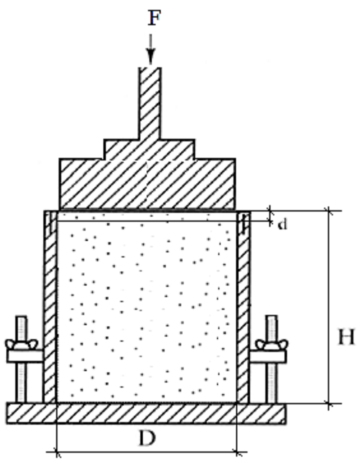



**Figure 14. Schematics of LWD on mold**

### 2.3.2. ***LWD on mold modulus calculation***

After testing the LWD at different drop heights and recording the peak deflections ($d_4$, $d_5$, and $d_6$), and peak applied load ($F_4$, $F_5$, $F_6$) for the three measurement drops at each drop height, the mold moduli ($E_{mold}$) were then calculated as follows:

**Equation 8**

$$E_{mold} = \left(1 - \frac{2\nu^2}{1-\nu}\right)\frac{4H}{\pi D^2}k$$

in which:

$\nu$ = Poisson's ratio (assumed 0.35 for all soils),

H = height of the mold (mold dimensions can be found in AASHTO T99),

D = the diameter of the plate or mold, and

k = stiffness calculated by dividing the measured applied load (F) to the average deflection (d) of the last 3 drops= $(F_4+F_5+F_6)/(d_4+d_5+d_6)$

**Important note:** It should be noticed that the modulus values reported by the LWD devices on the mold are automatically calculated using the Boussinesq formula (Equation 1) and should not be used for target modulus determination. The LWD deflections measured on the mold cannot be directly compared to the field deflections either.

The COV values for the deflections of the measurement drops were calculated and data sets having a COV of more than 10% were excluded from the target modulus calculations.

The $E_{mold}$ derived from the Equation 8 are designated as E_ZM, E_DM, and E_OM for the Zorn, Dynatest, and Olson LWDs, respectively. Each drop height on the mold corresponds to an applied pressure (P) which is normalized to the air pressure (101.325 kPa) in this study (P/Pa).

A two-variable linear or quadratic regression analysis is performed to define the moduli on mold as a function of MC (GWC) and normalized pressure (P/Pa). Then $E_{target}$ for each soil material was calculated by inputting the field's MC (if within acceptable MC range according to the state DOT's specifications) and the field normalized plate pressure into the regression equation.

The subgrade layer is assumed to be infinite in extent in the horizontal and downward vertical directions. The $E_{target}$ therefore can be compared to $E_{field}$ as a compaction QA criterion. However, for layered system, the $E_{target}$ should be corrected to consider the underlying layer's moduli (Section 2.3.3).

For the devices without a load cell that cannot measure the applied load from lower drop heights, the magnitude of the peak load is assumed correlated with the square root of drop height based on Section 2.3.4.

### 2.3.3. *Target modulus correction for finite layer thickness*

For base layers with finite thickness, the approach in the AASHTO Guide for the Design of Pavement Structures (1993) is employed. This approach considers a two-layer system (Figure 15) with a stiff top layer of thickness h (base) over subgrade of infinite depth. This method is based on the fundamental Boussinesq solution and Odemark's method of equivalent thickness (Grasmick et. al, 2014) and has been broadly implemented for the falling weight deflectometer testing (Schmalzer et. al, 2007).

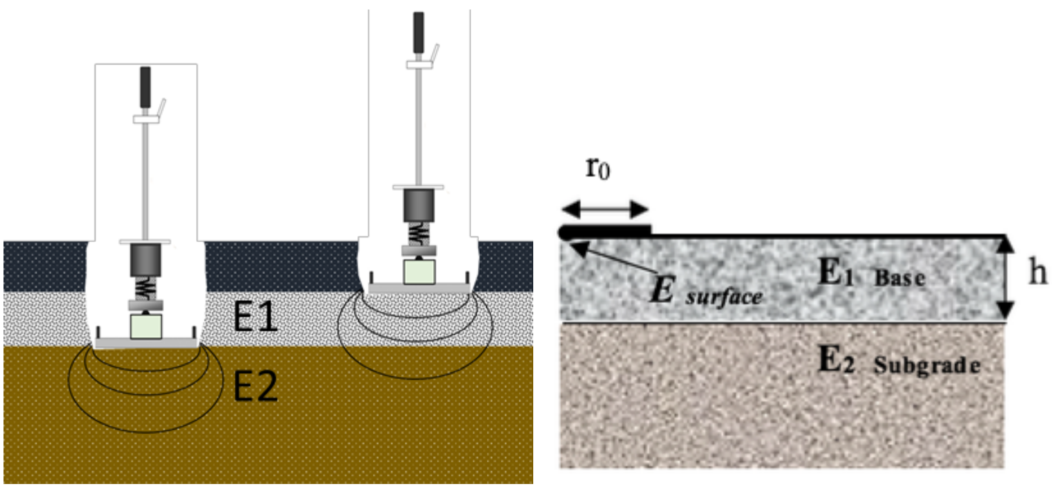



**Figure 15. Schematic of the two-layer system of subgrade with modulus $E_2$ overlain by base with thickness h and modulus $E_1$**

Thus, the total surface deflection directly under the circular load (LWD plate) is the combined deformations in the top and bottom layers. Burmister (1945) proposed a form of the following formula to calculate the surface modulus ($E_{surface}$):

**Equation 9**

$$E_{surface} = 1/\left\{\frac{1}{E_2\sqrt{1+\left(\frac{h}{r_0}\sqrt[3]{\frac{E_1}{E_2}}\right)^2}} + \frac{\left[1-\frac{1}{\sqrt{1+\left(\frac{h}{r_0}\right)^2}}\right]}{E_1}\right\}$$

in which:

$E_1$ = modulus of the top layer (GAB, base, etc.)

$E_2$ = modulus of the underlying layer (subgrade, fill, subbase, etc.)

$h$ = thickness of the top layer

$r_0$ = radius of the LWD plate

The target modulus values calculated from LWD on mold testing for GABs ($E_{target}=E_1$) should be corrected to $E_{surface}$ using Equation 9 as a function of the finite layer's thickness (h) and the underlying layer's modulus ($E_2$). Then $E_{surface}$ is the corrected target that can be compared to the field's modulus values ($E_{field}$) for QA purposes.

### 2.3.4. ***Force versus height assumptions for Zorn LWD***

The applied load (F) for the Zorn LWD at drops other than full height can be calculated using a single degree of freedom mechanical model. The potential energy (PE) stored in the falling weight due to gravity transforms to kinetic energy when releasing the weight from the height l. When the weight hits and deflects (Δl) the spring with stiffness (k) the energy is stored in the spring as elastic potential energy. According to the conservation of energy formula:

**Equation 10**

$$PE = m.g.l = \frac{1}{2}k.\Delta l^2 = \frac{1}{2}k\left(\frac{F}{k}\right)^2$$

therefore:

**Equation 11**

$$F = \sqrt{2.m.g.l.k}$$

Equation 11 was considered in estimating the applied force of Zorn LWD at heights other than the full height for target modulus calculation in the lab.

# 3. Chapter 3: Tested Sites and Material

Table 6 presents the field testing sites, visitation dates, and the quantity of collected data by NDG, LWDs, and oven drying moisture test for each project in the pooled fund study. A variety of geomaterial were tested and sampled including subgrades, GABs, embankment fill material, and cement modified soil. The test sites will be referenced by their state location name and soil type in this report. Depending on the construction schedule, data collection on some projects repeated multiple rounds on hourly intervals and on next lifts placed (depicted as R1, R2 and L1, L2 herein).

**Table 7. Material characteristics for evaluated field soils**

| Location and Soil Type | D30 | D10 | D60 | Cc | Cu | Atterberg Limits | | | Specific Gravity |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | LL | PL | PI | |
| Virginia, Phenix subgrade | 0.21 | 0.09 | 0.48 | 1.01 | 5.49 | - | - | non-plastic | 2.67 |
| MD 5, waste contaminated embankment | 0.85 | 0.19 | 3.85 | 0.97 | 19.83 | 22.30 | 19.35 | 2.90 | 2.21 |
| MD 5, subgrade | 0.79 | 0.40 | 9.42 | 0.16 | 23.54 | - | - | non-plastic | 2.69 |
| MD 337, deep GAB layer | 0.88 | 0.10 | 3.29 | 2.41 | 33.89 | - | - | non-plastic | 2.71 |
| MD 404, top subgrade | 0.37 | 0.26 | 0.56 | 0.96 | 2.13 | - | - | non-plastic | 2.37 |
| MD 404, local subgrade | 0.57 | 0.30 | 1.42 | 0.76 | 4.70 | - | - | non-plastic | 2.45 |
| MD 404, GAB | 0.43 | 0.11 | 3.74 | 0.46 | 34.00 | - | - | non-plastic | 2.41 |
| New York, embankment | 0.24 | 0.14 | 0.36 | 1.19 | 2.56 | - | - | non-plastic | 2.68 |
| Indiana, cement modified subgrade | 1.90 | 0.19 | 6.00 | 3.17 | 31.58 | 26.90 | 17.74 | 9.16 | 2.55 |
| Indiana, GAB | 3.10 | 0.31 | 9.81 | 3.14 | 31.35 | - | - | non-plastic | 2.83 |
| Missouri, subgrade | 1.01 | 0.33 | 8.44 | 0.37 | 25.74 | - | - | non-plastic | 2.50 |
| Missouri, GAB | 2.09 | 0.34 | 8.15 | 1.59 | 24.17 | - | - | non-plastic | 2.62 |
| Florida, Subgrade | 0.20 | 0.15 | 0.26 | 1.01 | 1.80 | - | - | non-plastic | 2.57 |
| Florida, Base | 0.45 | 0.23 | 2.49 | 0.34 | 10.66 | - | - | non-plastic | 2.46 |

Table 8

Table 7 summarizes the basic soil parameters including Atterberg limits, uniformity coefficient (Cu), coefficient of gradation (Cc), the soil particle diameter corresponding to 30% finer in the particle-size distribution (D30), the diameter corresponding to 60% finer in the particle-size distribution (D60), and the diameter in the particle-size distribution curve corresponding to 10% finer also defined as the effective size (D10) for each soil type. Almost all of the construction projects had non-plastic sand and well-graded gravel unbound materials.

Table 8 shows the AASHTO and Unified classification of the geomaterials for each project as determined from the basic soil parameter and sieve analysis results.

Detailed project descriptions, aerial views of project locations, soil gradation curves, and any important field conditions or limitations are provided in the Appendix B.

**Table 6. Testing date and quantities of field tests performed with different devices**

<table>
<tr><th></th><th>Location</th><th>Soil Type</th><th>Testing Date</th><th>NDG</th><th>Zorn LWD</th><th>Dynatest LWD</th><th>Olson LWD</th><th>Oven MC</th></tr>
<tr><td>1</td><td>Virginia</td><td>Phenix subgrade</td><td>07/30/15</td><td>15</td><td>30</td><td>30</td><td>30</td><td>10</td></tr>
<tr><td>2</td><td rowspan="6">Maryland</td><td>MD 5 waste contaminated embankment</td><td>08/5/15</td><td>20</td><td>60</td><td>60</td><td>0</td><td>40</td></tr>
<tr><td>3</td><td>MD 5 subgrade</td><td>08/13/15</td><td>30</td><td>90</td><td>90</td><td>90</td><td>60</td></tr>
<tr><td>4</td><td>MD 337, deep GAB layer</td><td>08/14/15</td><td>2</td><td>60</td><td>60</td><td>60</td><td>20</td></tr>
<tr><td>5</td><td>MD404 sand overlaying subgrade</td><td rowspan="2">10/15/15</td><td>10</td><td rowspan="2">30</td><td rowspan="2">30</td><td rowspan="2">30</td><td>10</td></tr>
<tr><td>6</td><td>MD 404 subgrade</td><td>10</td><td>10</td></tr>
<tr><td>7</td><td>MD 404 GAB</td><td>10/15/15</td><td>10</td><td>30</td><td>30</td><td>30</td><td>10</td></tr>
<tr><td>8</td><td>New York</td><td>Embankment (local subgrade)</td><td>08/20/15</td><td>40</td><td>90</td><td>90</td><td>90</td><td>30</td></tr>
<tr><td>9</td><td rowspan="2">Indiana</td><td>Cement modified subgrade</td><td>08/25/15</td><td>0</td><td>60</td><td>60</td><td>60</td><td>0</td></tr>
<tr><td>10</td><td>GAB</td><td>08/27/15</td><td>0</td><td>30</td><td>30</td><td>30</td><td>11</td></tr>
<tr><td>11</td><td rowspan="2">Missouri</td><td>Subgrade</td><td>-</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>12</td><td>GAB</td><td>08/26/15</td><td>30</td><td>90</td><td>90</td><td>90</td><td>30</td></tr>
<tr><td>13</td><td rowspan="2">Florida</td><td>Subgrade</td><td>10/20/15</td><td>10</td><td>30</td><td>30</td><td>0</td><td>10</td></tr>
<tr><td>14</td><td>Base</td><td>10/20/15</td><td>20</td><td>60</td><td>60</td><td>0</td><td>21</td></tr>
</table>

**Table 7. Material characteristics for evaluated field soils**

| Location and Soil Type | D30 | D10 | D60 | Cc | Cu | Atterberg Limits | | | Specific Gravity |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | LL | PL | PI | |
| Virginia, Phenix subgrade | 0.21 | 0.09 | 0.48 | 1.01 | 5.49 | - | - | non-plastic | 2.67 |
| MD 5, waste contaminated embankment | 0.85 | 0.19 | 3.85 | 0.97 | 19.83 | 22.30 | 19.35 | 2.90 | 2.21 |
| MD 5, subgrade | 0.79 | 0.40 | 9.42 | 0.16 | 23.54 | - | - | non-plastic | 2.69 |
| MD 337, deep GAB layer | 0.88 | 0.10 | 3.29 | 2.41 | 33.89 | - | - | non-plastic | 2.71 |
| MD 404, top subgrade | 0.37 | 0.26 | 0.56 | 0.96 | 2.13 | - | - | non-plastic | 2.37 |
| MD 404, local subgrade | 0.57 | 0.30 | 1.42 | 0.76 | 4.70 | - | - | non-plastic | 2.45 |
| MD 404, GAB | 0.43 | 0.11 | 3.74 | 0.46 | 34.00 | - | - | non-plastic | 2.41 |
| New York, embankment | 0.24 | 0.14 | 0.36 | 1.19 | 2.56 | - | - | non-plastic | 2.68 |
| Indiana, cement modified subgrade | 1.90 | 0.19 | 6.00 | 3.17 | 31.58 | 26.90 | 17.74 | 9.16 | 2.55 |
| Indiana, GAB | 3.10 | 0.31 | 9.81 | 3.14 | 31.35 | - | - | non-plastic | 2.83 |
| Missouri, subgrade | 1.01 | 0.33 | 8.44 | 0.37 | 25.74 | - | - | non-plastic | 2.50 |
| Missouri, GAB | 2.09 | 0.34 | 8.15 | 1.59 | 24.17 | - | - | non-plastic | 2.62 |
| Florida, Subgrade | 0.20 | 0.15 | 0.26 | 1.01 | 1.80 | - | - | non-plastic | 2.57 |
| Florida, Base | 0.45 | 0.23 | 2.49 | 0.34 | 10.66 | - | - | non-plastic | 2.46 |

**Table 8. Test site locations and soil types**

| | Location | Soil Type | AASHTO Classification | Unified Classification | |
|---|---|---|---|---|---|
| 1 | Virginia | Subgrade | A-3 | SP-SM | Poorly graded sand with silt |
| 2 | Maryland | MD5 Waste contaminated embankment | A-1-a | SW | Well graded sand with gravel |
| 3 | | MD5 Subgrade | A-2-7 | SP | Poorly graded sand with gravel |
| 4 | | MD 337, Deep GAB | A-2-7 | GW-GM | Well graded gravel with silt and sand |
| 5 | | MD404 sand overlaying Subgrade | A-2-7 | SP | Poorly graded sand |
| 6 | | MD 404 Subgrade | A-2-6 | SP | Poorly graded sand |
| 7 | | MD 404 Base | A-2-7 | GP-GM | Poorly graded gravel with silt and sand |
| 8 | New York | Embankment | A-3 | SP | Poorly graded sand |
| 9 | Indiana | Cement modified Subgrade | A-2-4 | SW | Well graded sand with gravel |
| 10 | | Virgin Subgrade | A-2-4 | SW-SM | Well graded sand with silt and gravel |
| 11 | | Base | A-1-a | GW | Well graded gravel with sand |
| 12 | Missouri | Subgrade | A-3 | SP | Poorly graded sand with gravel |
| 13 | | Base | A-3 | GW | Well graded gravel with sand |
| 14 | Florida | Subgrade | A-2-7 | SP | Poorly graded sand |
| 15 | | Base | A-3 | SP | Poorly graded gravel with sand |

# 4. Chapter 4: Results and Discussion

Table 9 presents the average weather condition data and soil surface temperature during the field construction and testing. A variety of temperature, humidity, and wind speed combinations were encountered.

**Table 9. Soil surface temperatures and weather conditions for the field sites**

| **Project Location** | **Soil Temperature (°C)** | **Wind Speed (km/hr)** | **Air Temperature (°C)** | **Humidity (%)** | **Evaporation Rate ($kg/m^2/hr$)** |
|---|---|---|---|---|---|
| VA subgrade | 42 | 0-2.7-3.4* | 33 | 64.0% | 0.41 |
| MD 5 embankment | 32 | 6 | 30 | 44.5% | 0.65 |
| MD 5 subgrade | 31 | 4-9 | 25 | 53.3% | 0.61-0.77* |
| MD 337 | 34 | 8-9 | 28.5 | 39.9% | 0.67-0.75 |
| MD 404 | 14 | 0-3 | 15 | 71.0% | 0.04 |
| NY embankment | 28 | 4-9 | 29.1 | 61.0% | 0.25-0.53 |
| Missouri | 25 | 0 | 25 | 54.0% | 0.13 |
| Indiana | 22 | 0-10 | 18.6 | 61.1% | 0.11-0.34 |
| Florida | 20 | 3-10 | 24.7 | 60.0% | 0.05-0.08 |

* Magnitude varied in that range.

## 4.1. Evaluation of MC devices in the field

The GWC results from the NDG and oven-drying method are summarized in Figure 16 and Figure 17 respectively. The standard deviation of moisture contents at each site is shown as error bars in the figures. The highest spatial variability in the measured water content was observed at the Virginia subgrade site which was tested a week after compaction. This confirms the importance of testing right after compaction to be able to evaluate the uniformity in compaction. The MD5 embankment soil contained large pieces of waste material such as metal cans, rubber and glass that affected the NDG readings, and consequently this material was excluded from this study. Appendix C provides the average, standard deviation and COV values of the measurements for all test sites.

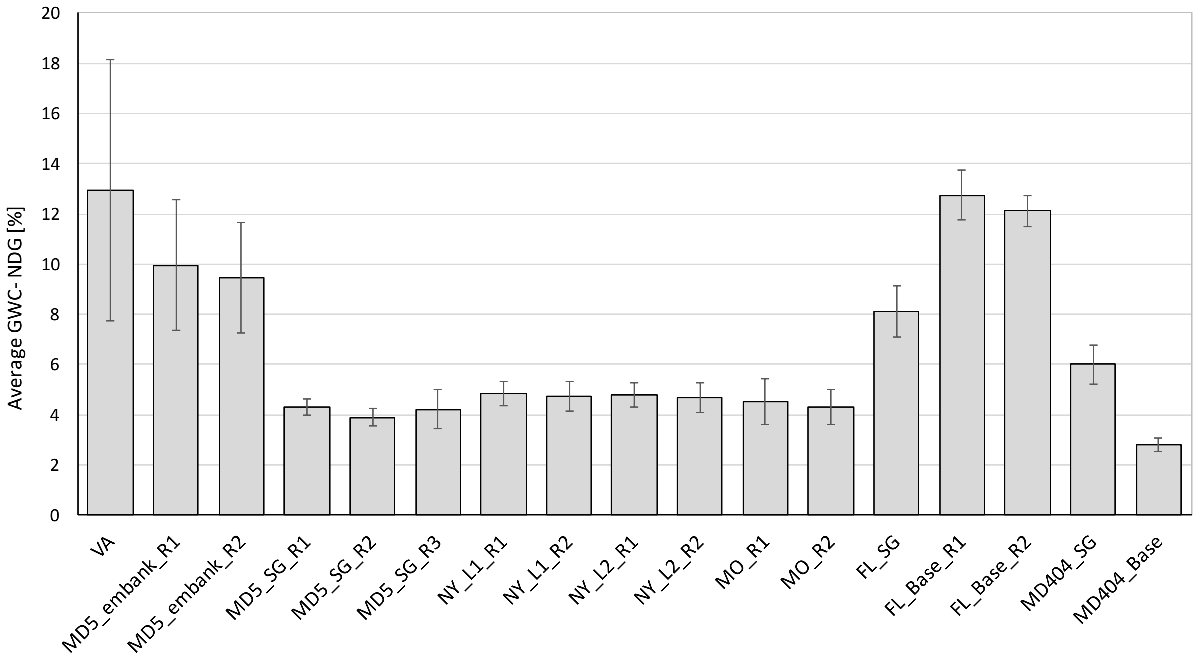



**Figure 16. Summary of GWC measured by NDG at different sites (SG:subgrade, L: Lift, R:Round)**

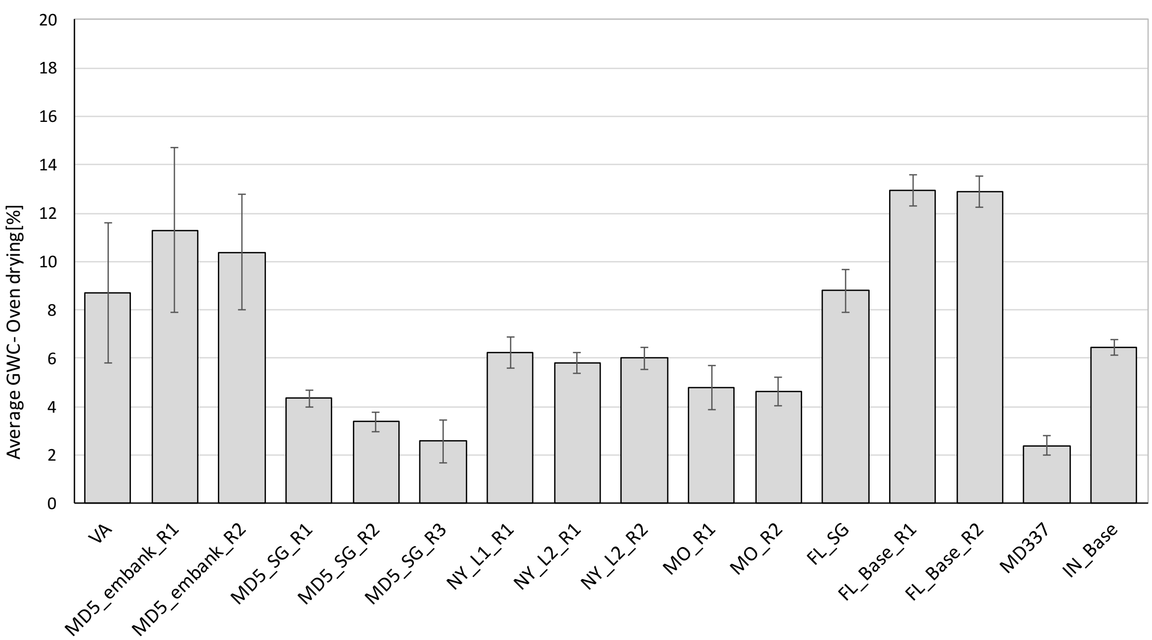



**Figure 17. Summary of GWC by oven drying method for different sites (SG:subgrade, L: Lift, R:Round)**

The moisture contents measured with the NDG are compared with the oven drying moisture contents in Figure 18. Good correlation is observed overall, with the NDG overestimating the GWC only by 7% on average.

The spatial COV of water content measured by NDG was compared to the oven dried values for all sites and rounds of testing in Figure 19. In most cases, the NDG testing shows higher spatial variability in measured water content compared to the oven method.

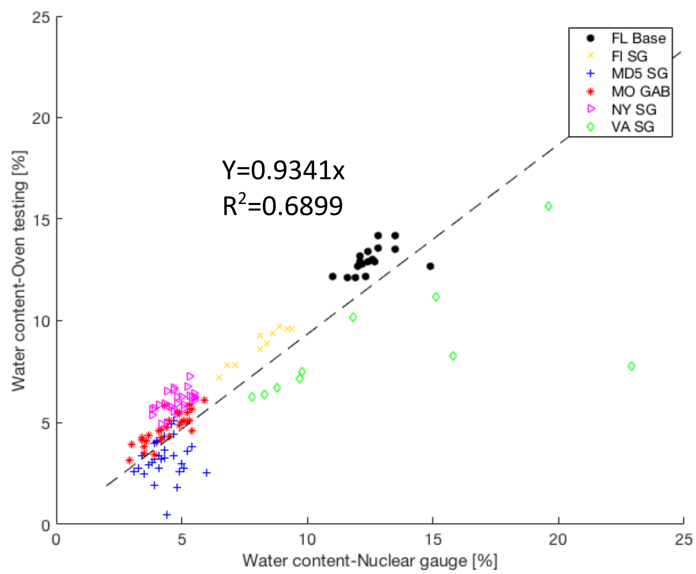



**Figure 18. Gravimetric water content obtained from oven drying method vs NDG**

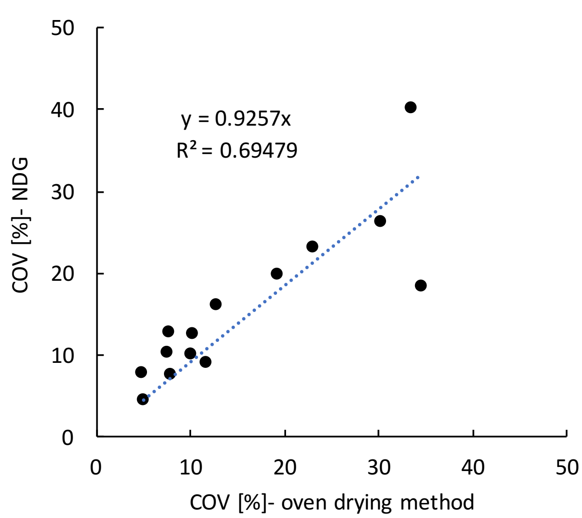



**Figure 19. Spatial COV of water content for NDG versus oven drying method**

The Ohaus MB45 moisture analyzer was also evaluated in a few test sites. The moisture analyzer was terminated manually when the GWC versus time curve became flat. The drying time lasted between 10 to 15 minutes for the MD337 GAB and MD5 subgrade and 30 to 35 minutes for the IN cement modified subgrade. Water content measurements with the Ohaus device were not performed at some sites to avoid undue delays in the construction process.

Figure 20 shows the very good correlation between the average GWC measured by the Ohaus device for the Maryland sites and the corresponding oven drying water contents after applying the 1.11 correction factor.

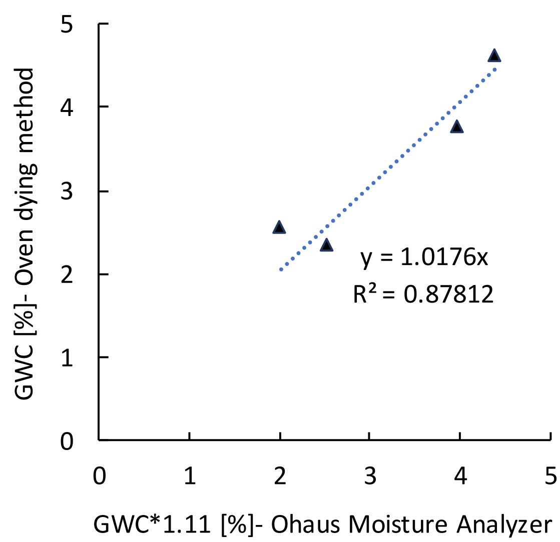



**Figure 20. Average GWC obtained by Ohaus moisture analyzer versus oven drying method**

## 4.2. LWD modulus and NDG PC measurements

Figure 21, Figure 22, and Figure 23 present the surface modulus results measured by Zorn, Olson, and Dynatest LWD respectively. The standard deviation of the measured moduli at different stations were calculated to represent the spatial variability, which is depicted as error bars for each site.

Factors contributing to the spatial variability include soil type, LWD brand and configuration, degree of compaction, saturation, evenness, and contact stress. Overall, the Dynatest LWD exhibited the highest average spatial COV for the sites in this study. The COV varied between 15% to 95% for subgrade soils and 13.97% to 85.6% for base material. The Zorn LWD showed the lowest average COV, varying from 10% to 80% for subgrade soils and 12% to 39% for base soils (Table 10). Appendix C presents the detailed results for the LWD measurements at each site.

The Zorn LWD assumes a peak applied load of 7.07 kN for all drops and all soils type, hence the variability in the modulus is attributed to the surface deflection COV only (deflection sensor on the plate). The Dynatest and Olson LWDs measure the applied load, which varies slightly at different stations even for the same soil. Consequently, the variability in the moduli reflects a combination of variability of applied load and measured deflection for the Olson and Dynatest LWDs.

The Dynatest LWD also exhibits more sensitivity to the surface drying of a compacted layer (Afsharikia, 2017) and shows an increasing trend in modulus when testing at hourly intervals. This trend can be noticed in Figure 23 for the MD5 subgrade, the MO base, and the FL base materials. This could be due to the direct contact of Dynatest deflection rod with the compacted surface.

Figure 24 summarizes the Percent Compaction (PC) values for each test site with error bars as standard deviation (see also Appendix C). The MDD for most soils were determined by the state lab for each project and input by the NDG operator on site. For the sites where the MDD data was not pre-determined, Proctor testing was performed in the lab according to AASHTO T 99 or T-180 and then the PC was calculated.

The COV of PC ranged from a minimum 1.3% for the FL base to maximum of 4.6% for the VA subgrade material. INDOT does not use NDG tests for routine compaction QA and instead performs proof rolling with a fully loaded tri-axle truck to evaluate compaction quality.

**Table 10. Variation of moduli for different LWDs**

| | | Zorn LWD | | Dynatest LWD | | Olson LWD | |
|---|---|---|---|---|---|---|---|
| **Layer** | **Parameter** | **Modulus [Mpa]** | **COV [%]** | **Modulus [Mpa]** | **COV [%]** | **Modulus [Mpa]** | **COV [%]** |
| Subgrade | Min. | 10.401 | 10.157 | 14.881 | 15.166 | 19.299 | 15.476 |
| | Max. | 82.240 | 80.187 | 474.580 | 95.003 | 101.530 | 71.446 |
| | Avg. | 39.683 | 33.060 | 128.663 | 54.844 | 51.760 | 34.831 |
| Base | Min. | 35.122 | 12.454 | 60.762 | 13.975 | 46.834 | 11.207 |
| | Max. | 73.261 | 38.787 | 203.105 | 85.661 | 82.826 | 33.627 |
| | Avg. | 56.611 | 21.540 | 130.481 | 35.870 | 63.477 | 25.925 |

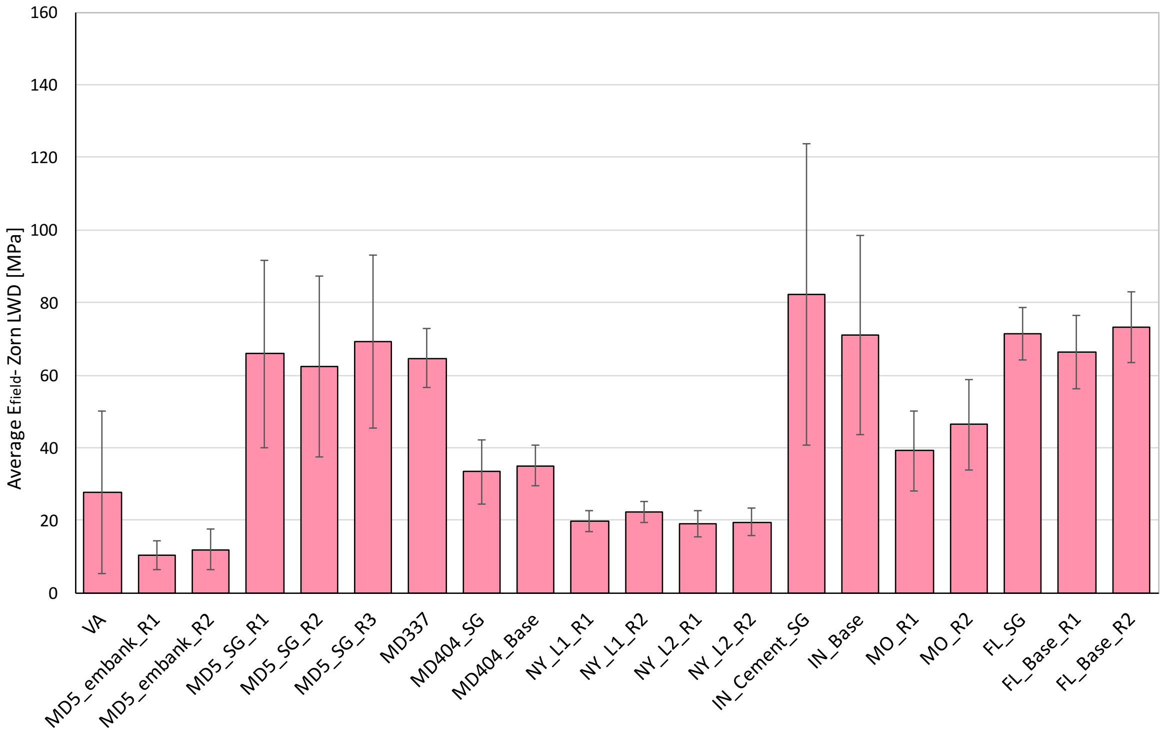



**Figure 21. Summary of Zorn LWD moduli measurements at different sites (SG:subgrade, L:Lift, R:Round)**

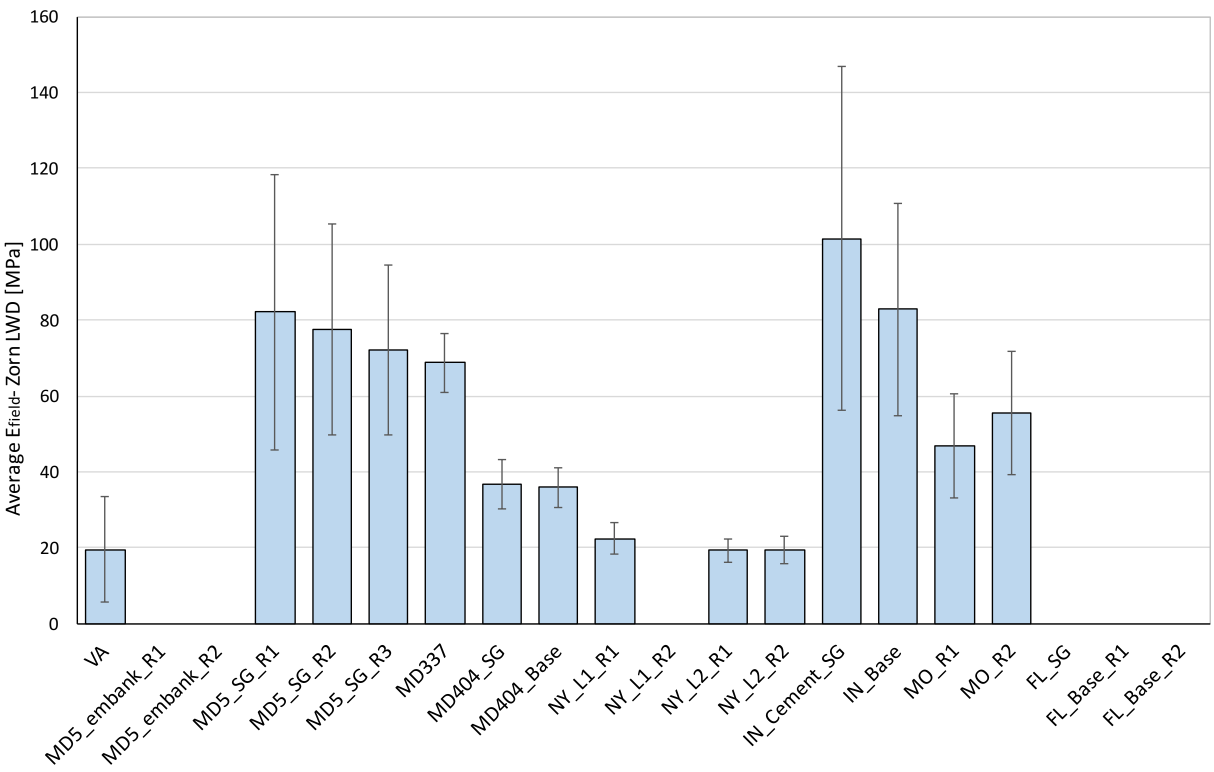



**Figure 22. Summary of Olson LWD moduli measurements at different sites (SG:subgrade, L:Lift, R:Round)**

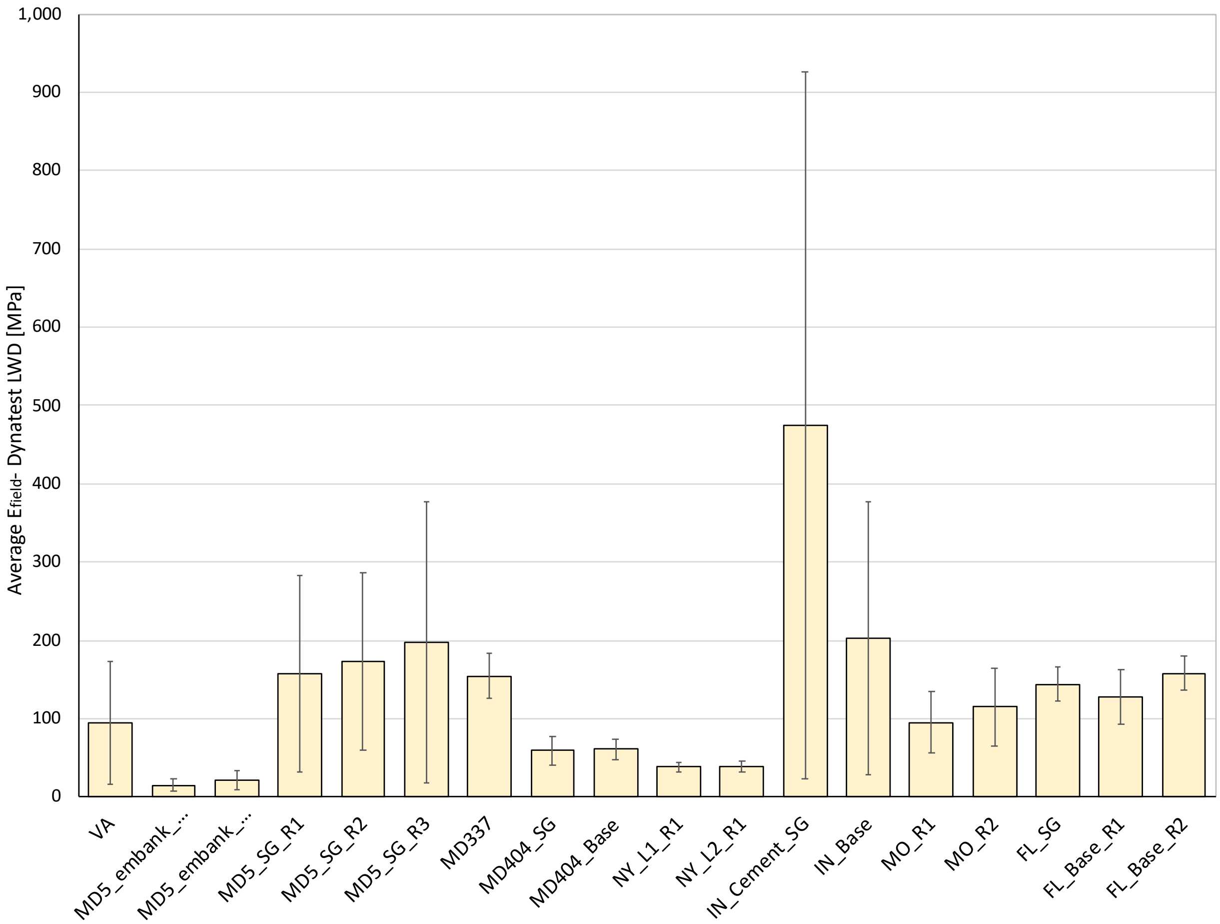



**Figure 23. Summary of Dynatest LWD moduli measurements at different sites (SG:subgrade, L:Lift, R:Round)**

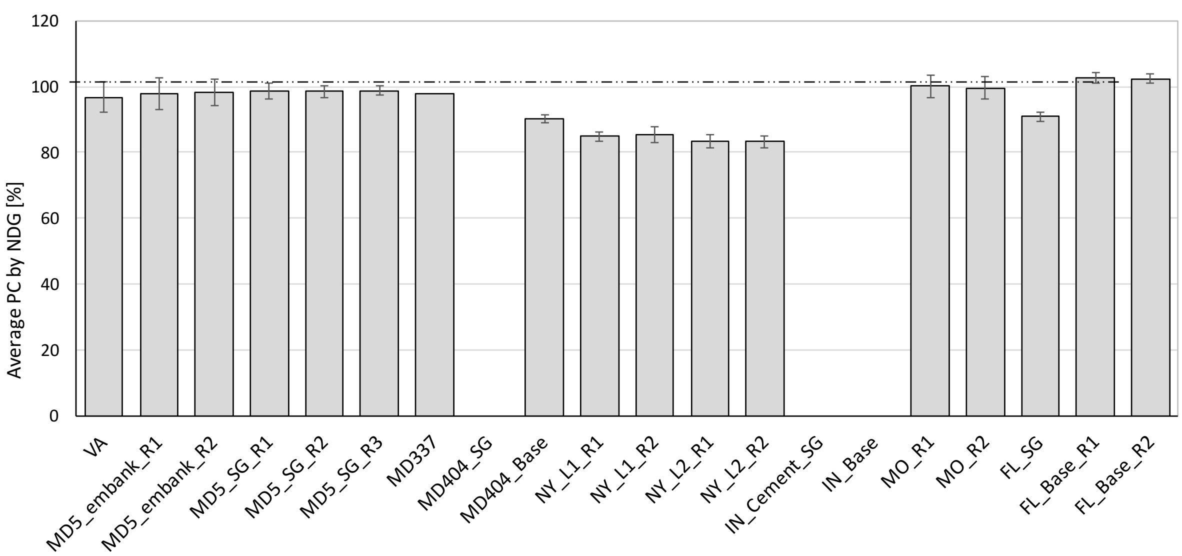


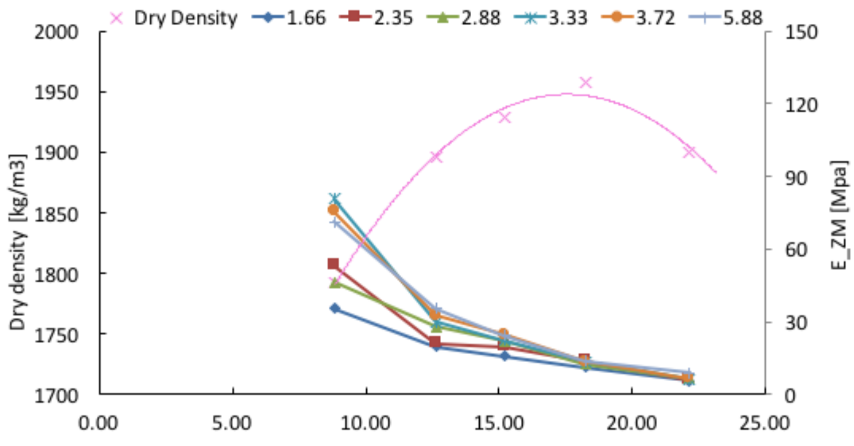

**Figure 24. Summary of percent compaction measured by NDG in the field**

## 4.3. Results of LWD on mold testing

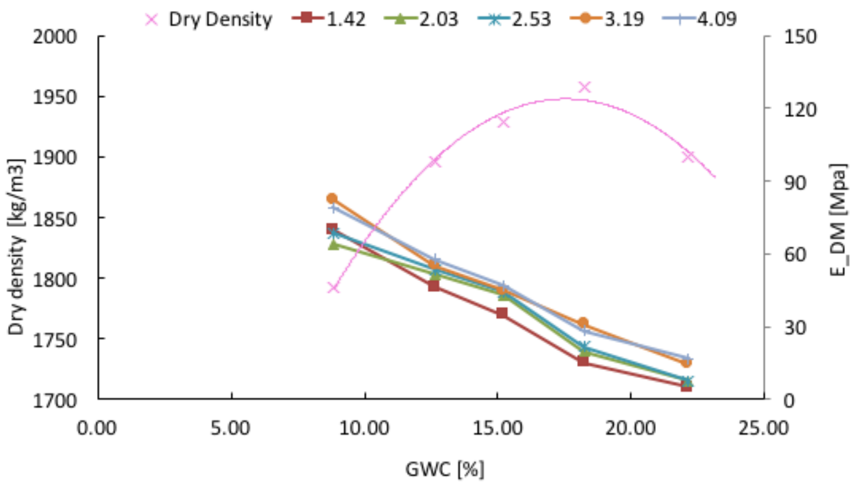
Figure 25 to Figure 34 present the results of the LWD on mold testing superimposed on the dry density versus water content curves for every field material and LWD type. The legend shows the P/Pa corresponding to each drop height.

Due to limited quantities of material, the soil from the test sites had to be re-used for specimen compaction. When the soil material is fragile in character, the grain size distribution may be altered by repeated compaction. It is recommended to use a separate new soil sample for each compaction test.

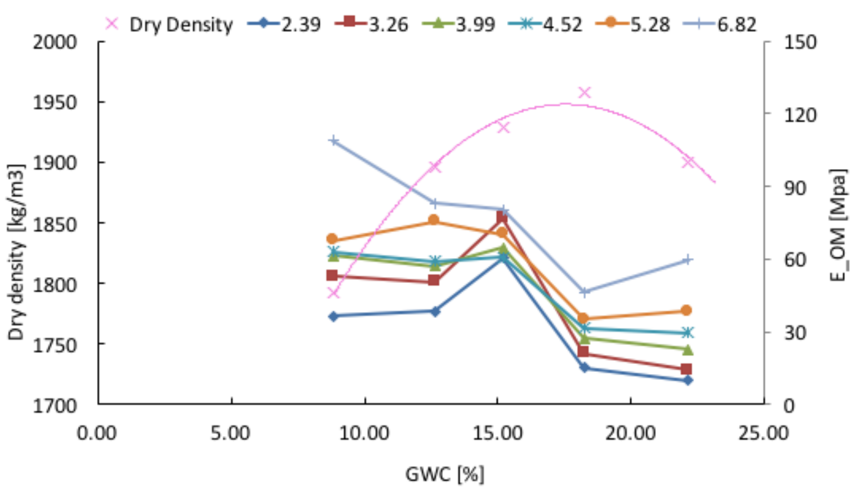
LWD testing for water contents very wet of the OMC was impossible due to substantial permanent deformations and excessive water drainage from the mold during the testing. The LWD moduli on mold sometimes increased for specimens compacted wet of OMC due to pore water pressure built up. These data were excluded from the target calculation.




A)

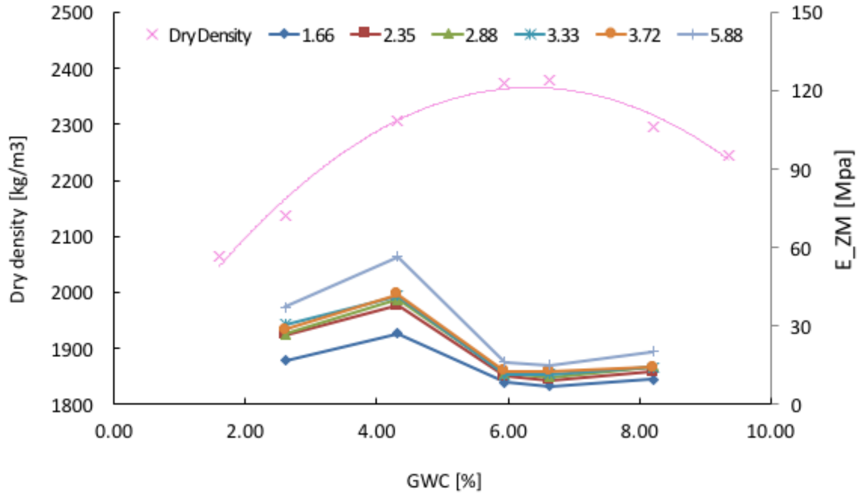



B)

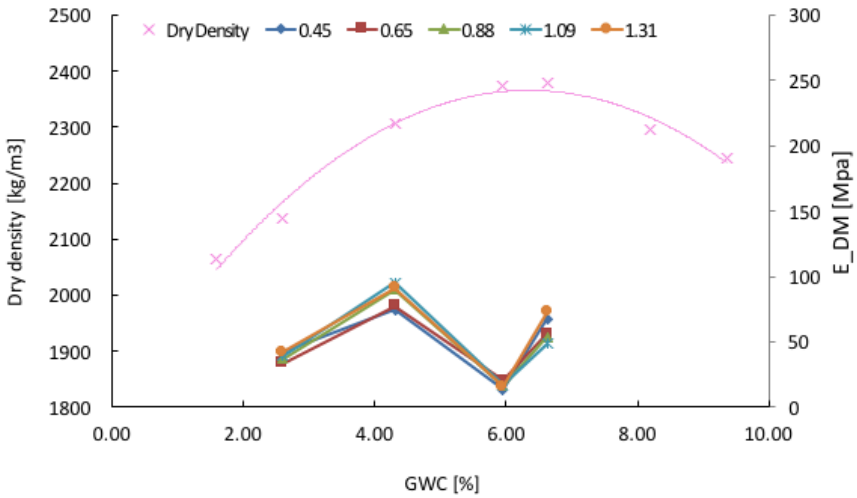



C)

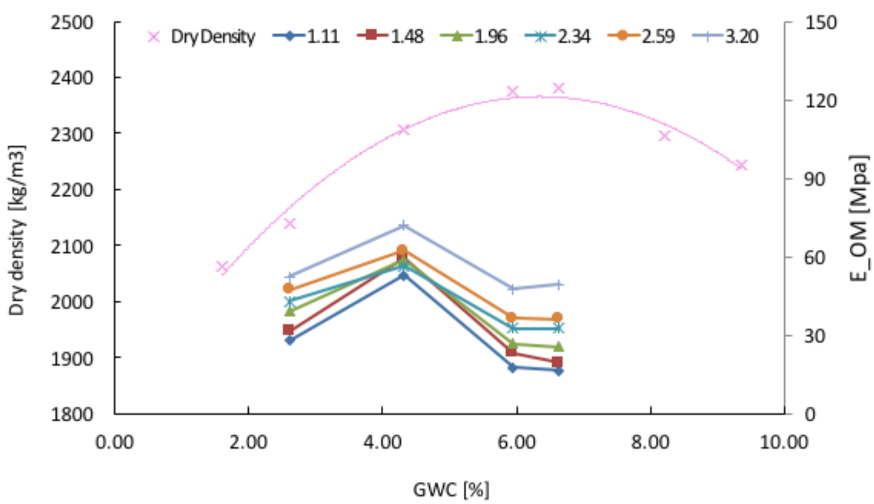
**Figure 25. LWD modulus on mold superimposed on dry density versus GWC for VA21a soil at variable P/Pa for (A) Zorn, (B) Dynatest, and (C) Olson LWDs**




A)

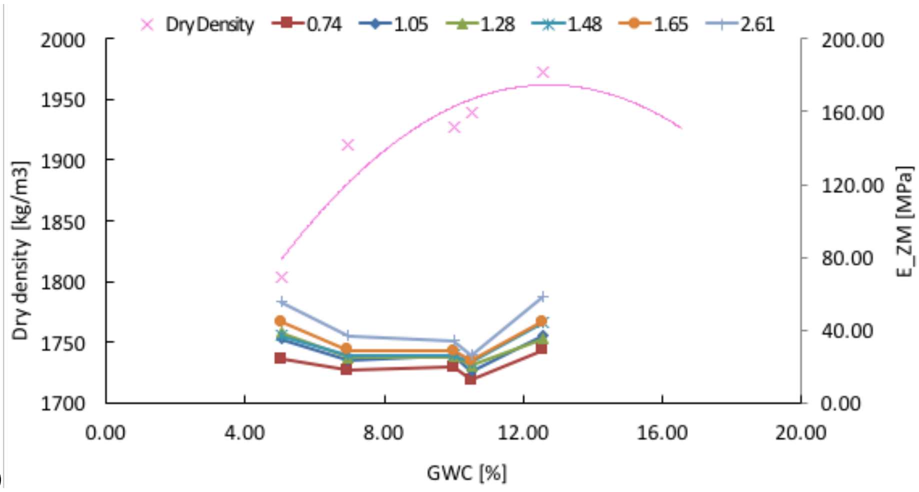



B)

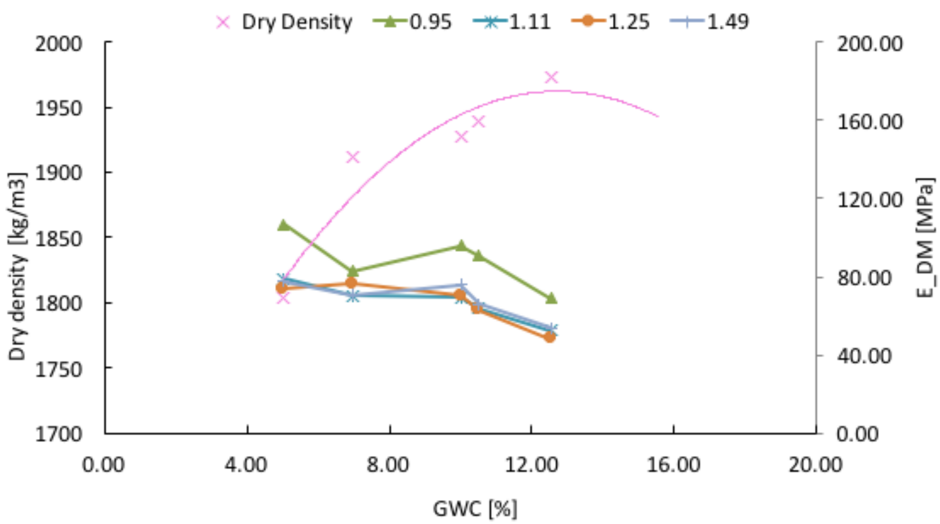



C)

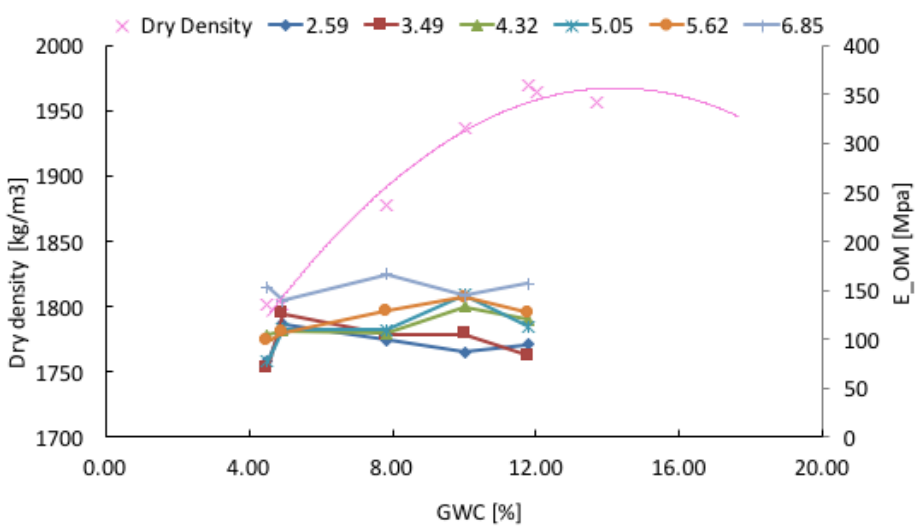
**Figure 26. LWD modulus on mold superimposed on dry density versus GWC for MD5 subgrade at variable P/Pa for (A) Zorn, (B) Dynatest, and (C) Olson LWDs**




A)




B)




C)

**Figure 27. LWD modulus on mold superimposed on dry density versus GWC for NY embankment soil at variable P/Pa for (A) Zorn, (B) Dynatest, and (C) Olson LWDs**

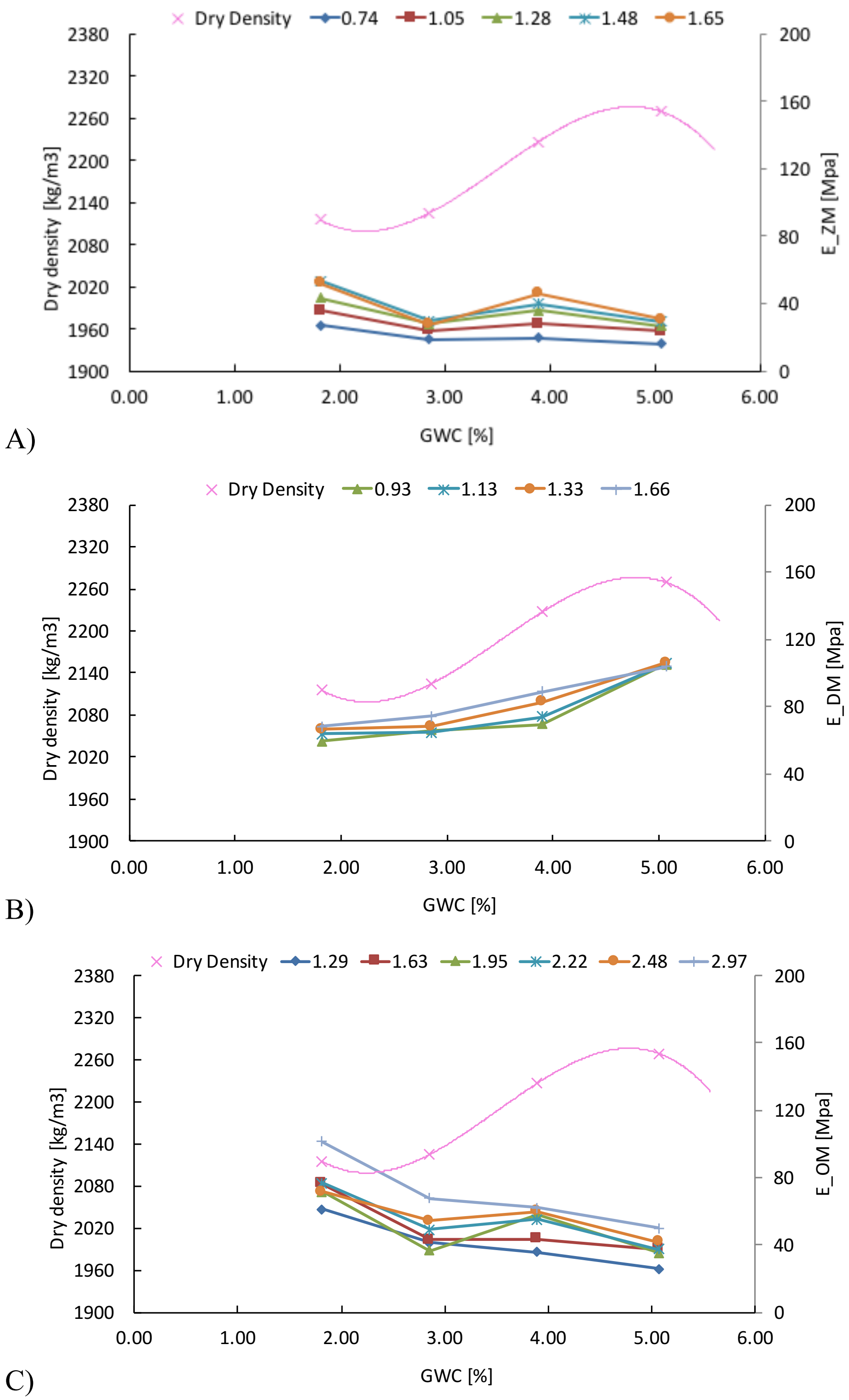
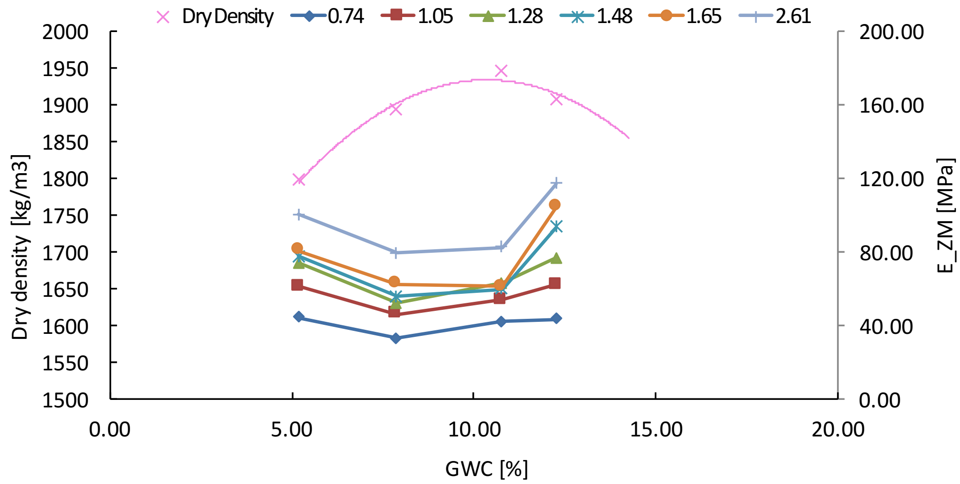
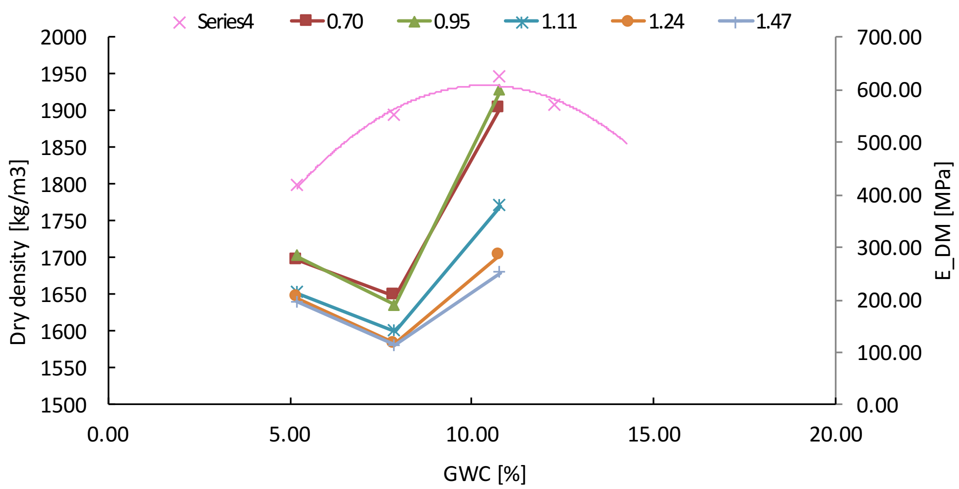



**Figure 28. LWD modulus on mold superimposed on dry density versus GWC for MD337 base at variable P/Pa for (A) Zorn, (B) Dynatest, and (C) Olson LWDs**




A)

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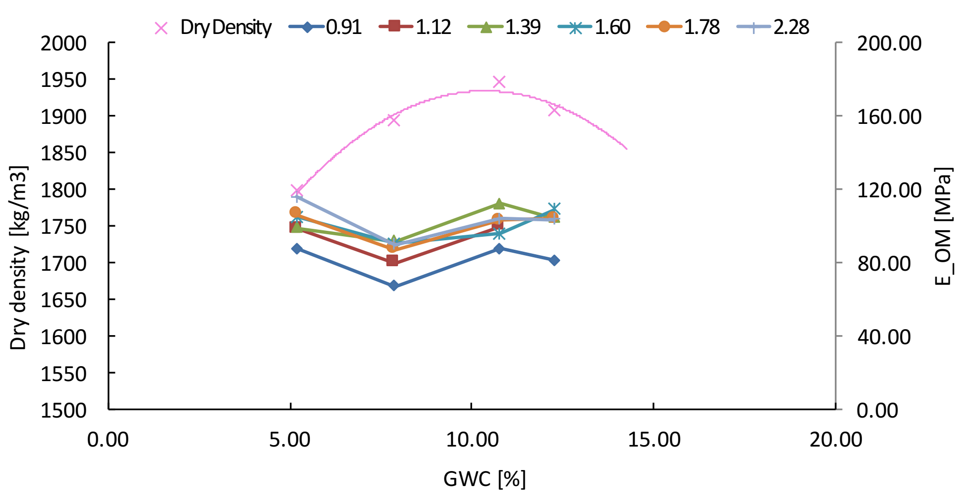



C)

**Figure 29. LWD modulus on mold superimposed on dry density versus GWC for FL subgrade at variable P/Pa for (A) Zorn, (B) Dynatest, and (C) Olson LWDs**

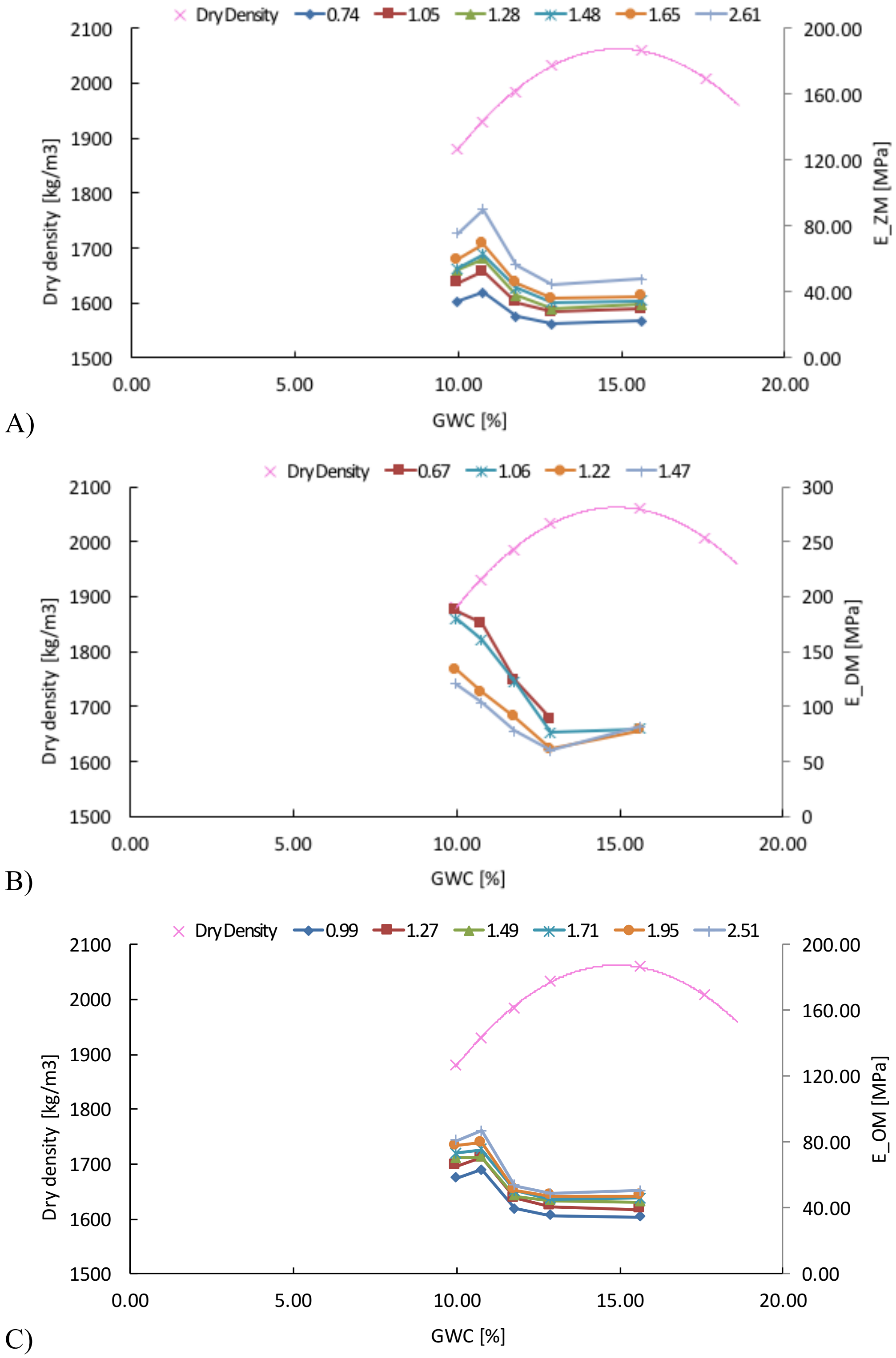
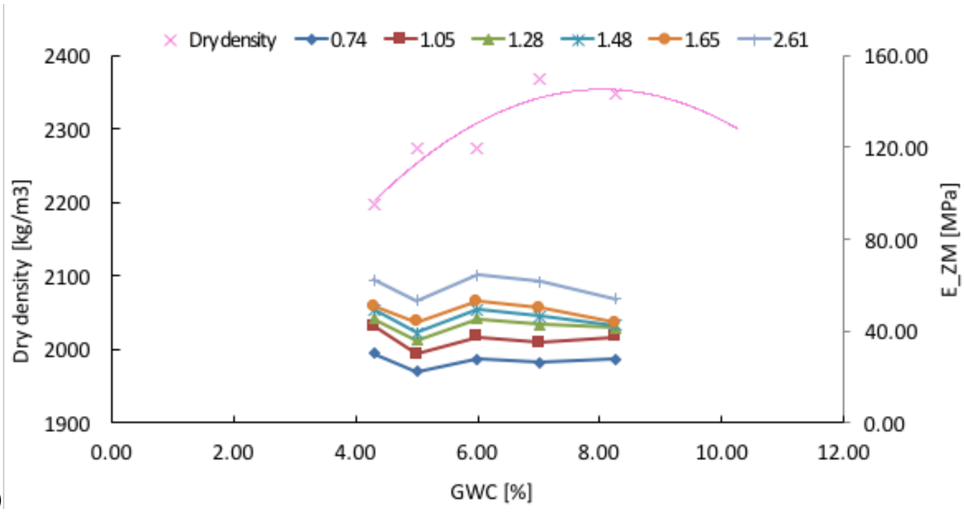
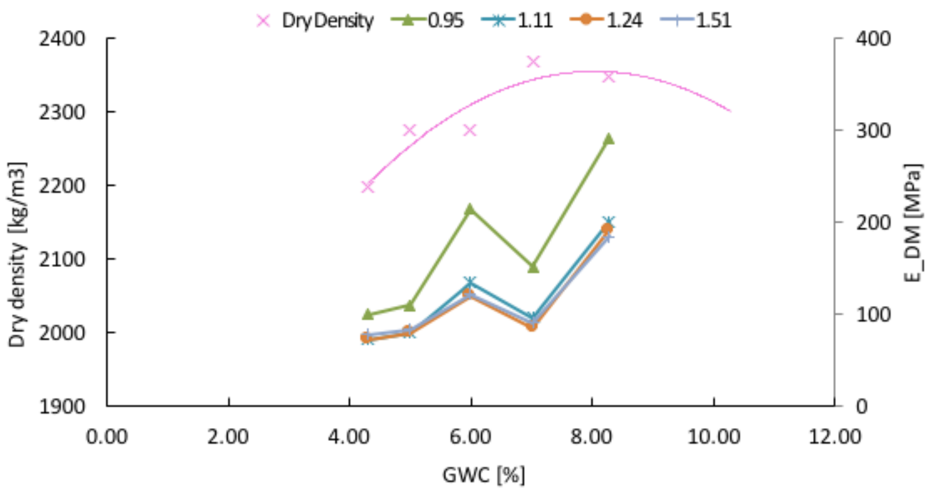


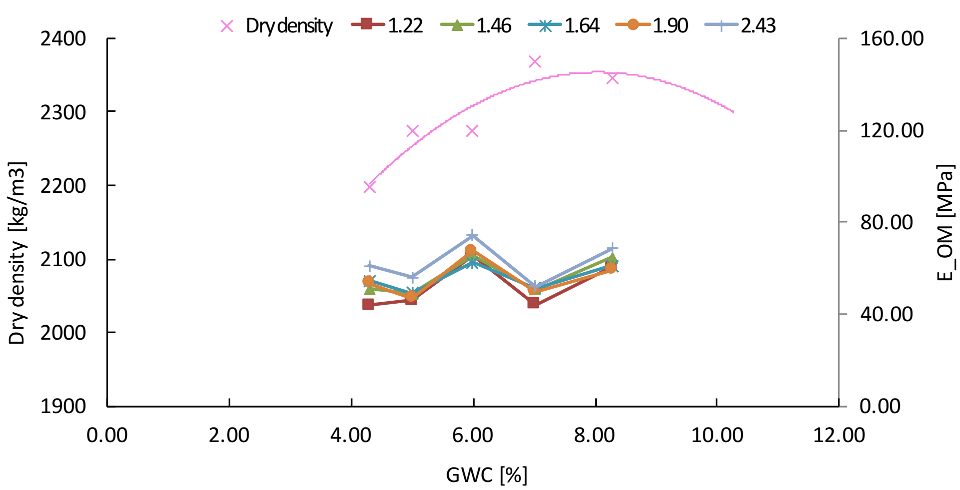

**Figure 30. LWD modulus on mold superimposed on dry density versus GWC for FL base at variable P/Pa for (A) Zorn, (B) Dynatest, and (C) Olson LWDs**




A)

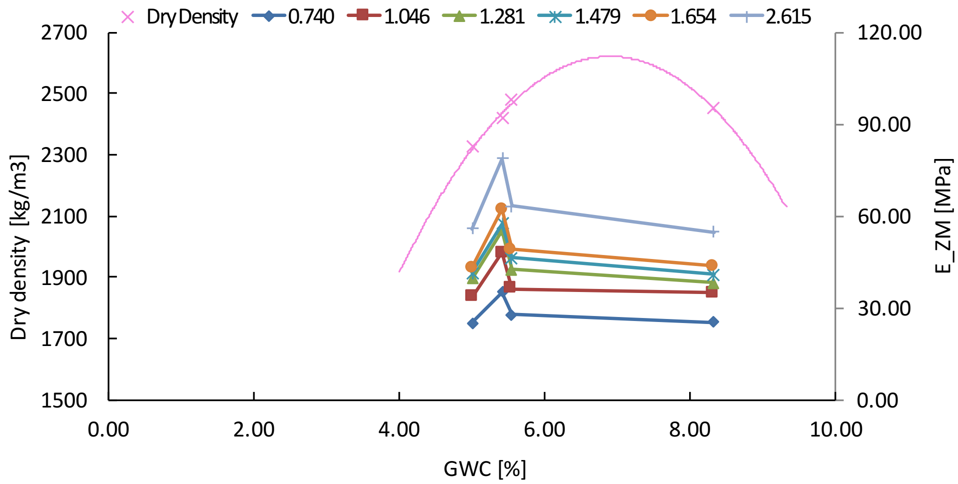



B)

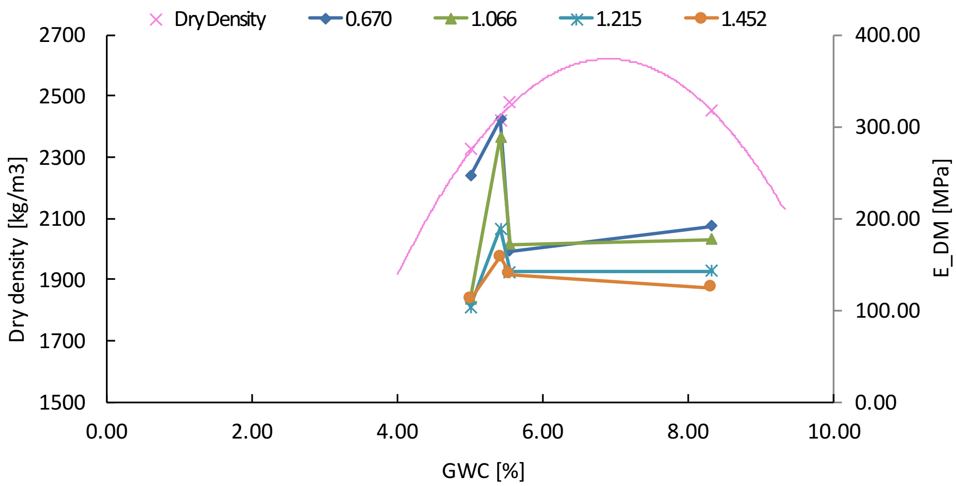



C)

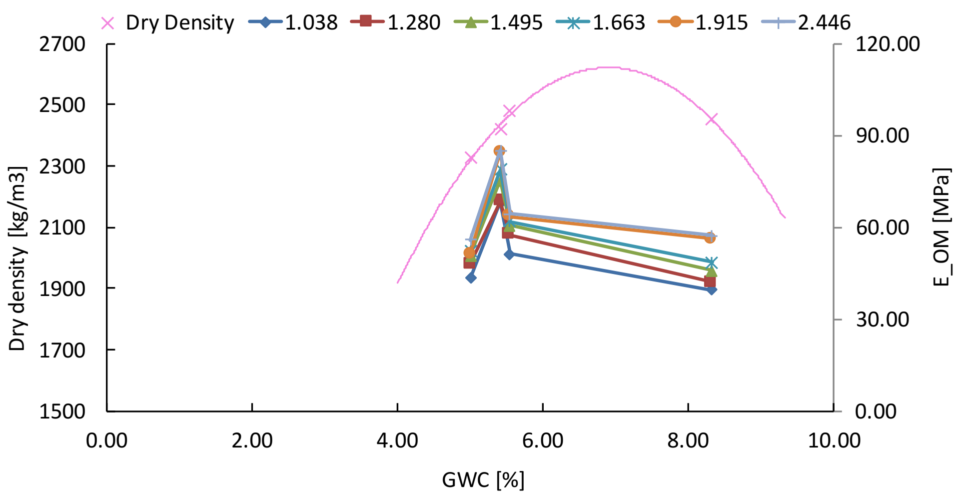
**Figure 31. LWD modulus on mold superimposed on dry density versus GWC for MD404 base at variable P/Pa for (A) Zorn, (B) Dynatest, and (C) Olson LWDs**




A)

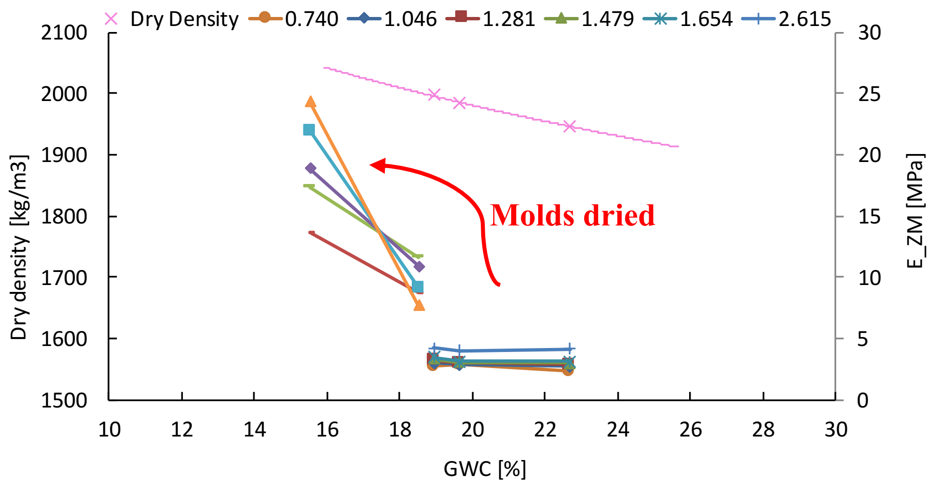



B)

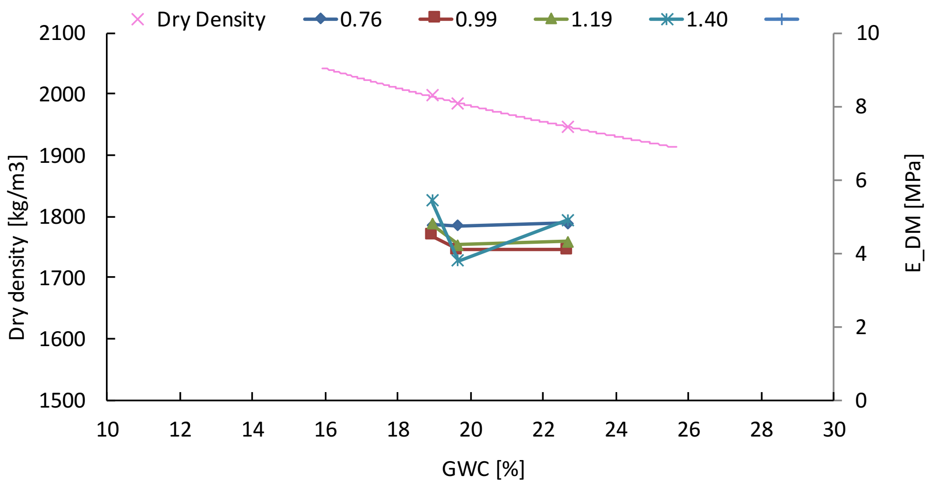



C)

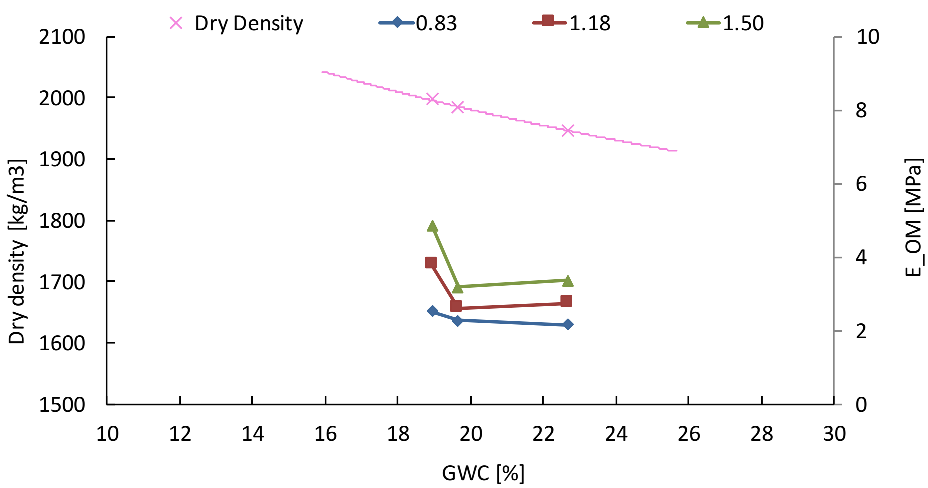
**Figure 32. LWD modulus on mold superimposed on dry density versus GWC for IN base at variable P/Pa for (A) Zorn, (B) Dynatest, and (C) Olson LWDs**




A)




B)




C)

**Figure 33. LWD modulus on mold superimposed on dry density versus GWC for IN cement modified subgrade at variable P/Pa for (A) Zorn, (B) Dynatest, and (C) Olson LWDs**

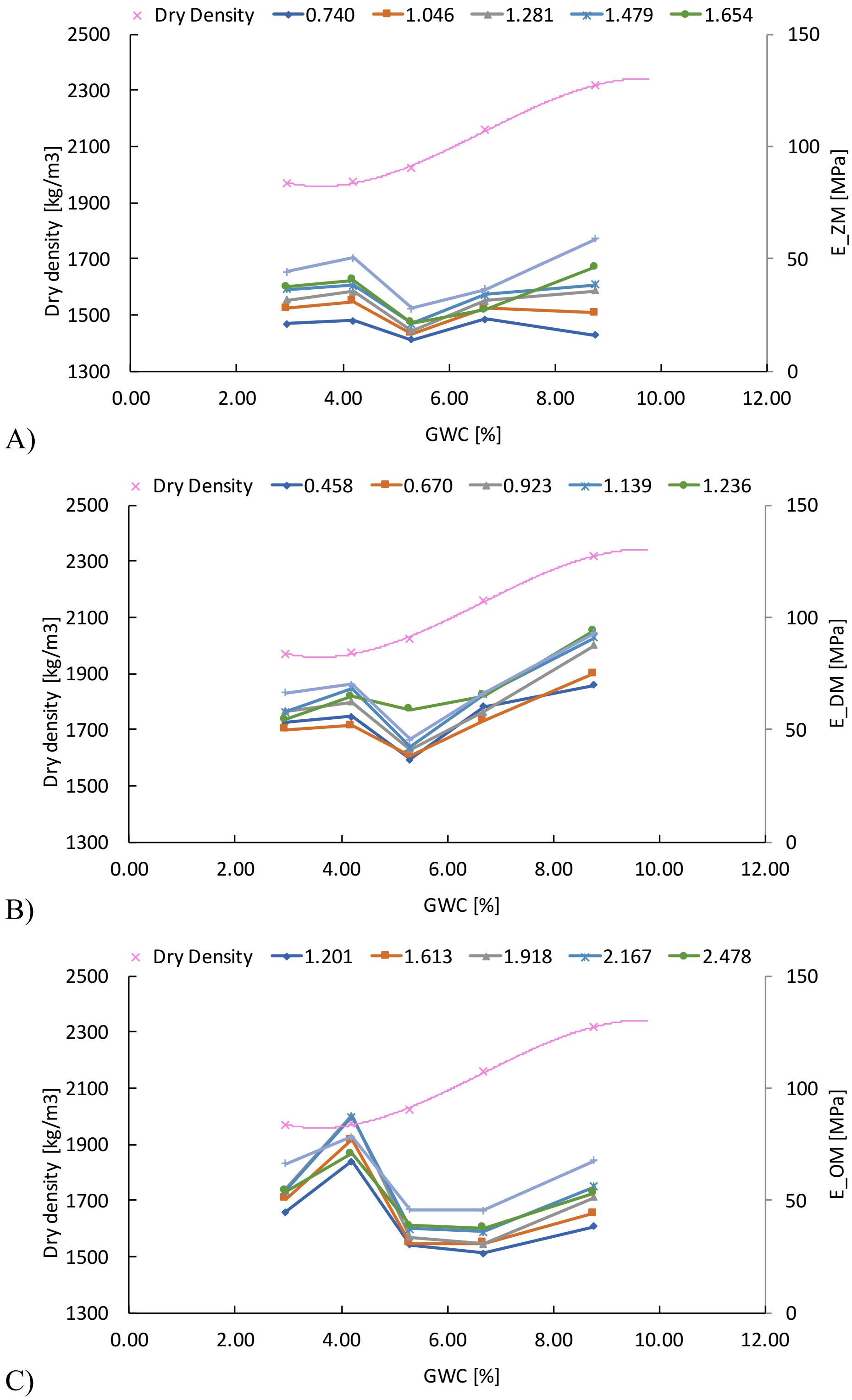



**Figure 34. LWD modulus on mold superimposed on dry density versus GWC for MO base at variable P/Pa for (A) Zorn, (B) Dynatest, and (C) Olson LWDs**

## 4.4. Field to target modulus ratio versus percent compaction

PC measured by NDG in the field verification sites is used as a criterion for compaction quality. The ratio of the field modulus to the calculated target modulus ($E_{field}/E_{target}$) is compared to PC in Figure 34 to Figure 39. When the average $E_{field}/E_{target}$ values fall in the upper right quadrant, the compacted layer satisfied both the density and modulus requirements.

The MD5 subgrade, NY embankment, and MD337 base materials were tested immediately after compaction with minimal drying at the time of testing. The MD5 subgrade (Figure 35) and MD337 base (Figure 37) are well-compacted layers with PC greater than 97% as required by MDOT SHA. The average $E_{field}/E_{target}$ are corresponding equal to or greater than 1 for all three LWD types, confirming the adequate compaction. The NY embankment soil was under compacted with an average PC of about 84% (Figure 36). The field to target modulus ratios were considerably less than 1 for both lifts, confirming the inadequate compaction.

The $E_{field}/E_{target}$ values for the MD404 base and FL base soils are compared to PC in Figure 38 and Figure 39, respectively. LWD testing was performed prior to base placement on the compacted subgrade for these sites in order to determine the subgrade modulus values for use in Equation 9 to correct the target values for the finite base layer thickness. The well-compacted FL base material passed both the PC and $E_{field}/E_{target}$ criteria, whereas the MD404 failed to meet both since the material was compacted too dry (also failing to meet the MC criteria).

A)

B)

C)

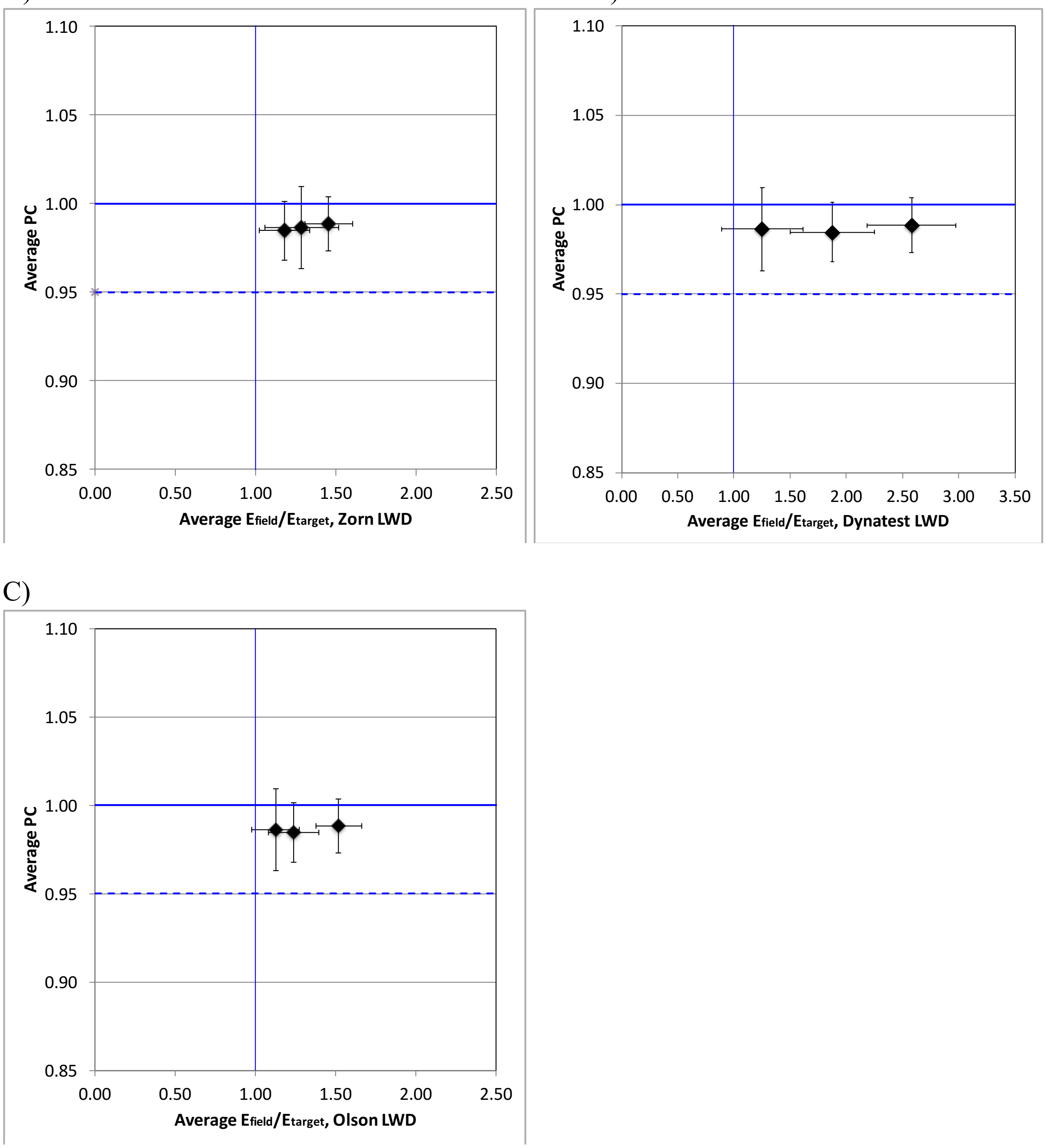



**Figure 35. Average PC versus average $E_{field}$ to $E_{target}$ ratio for MD5 subgrade for (A) Zorn, (B) Dynatest, and (C) Olson LWDs**

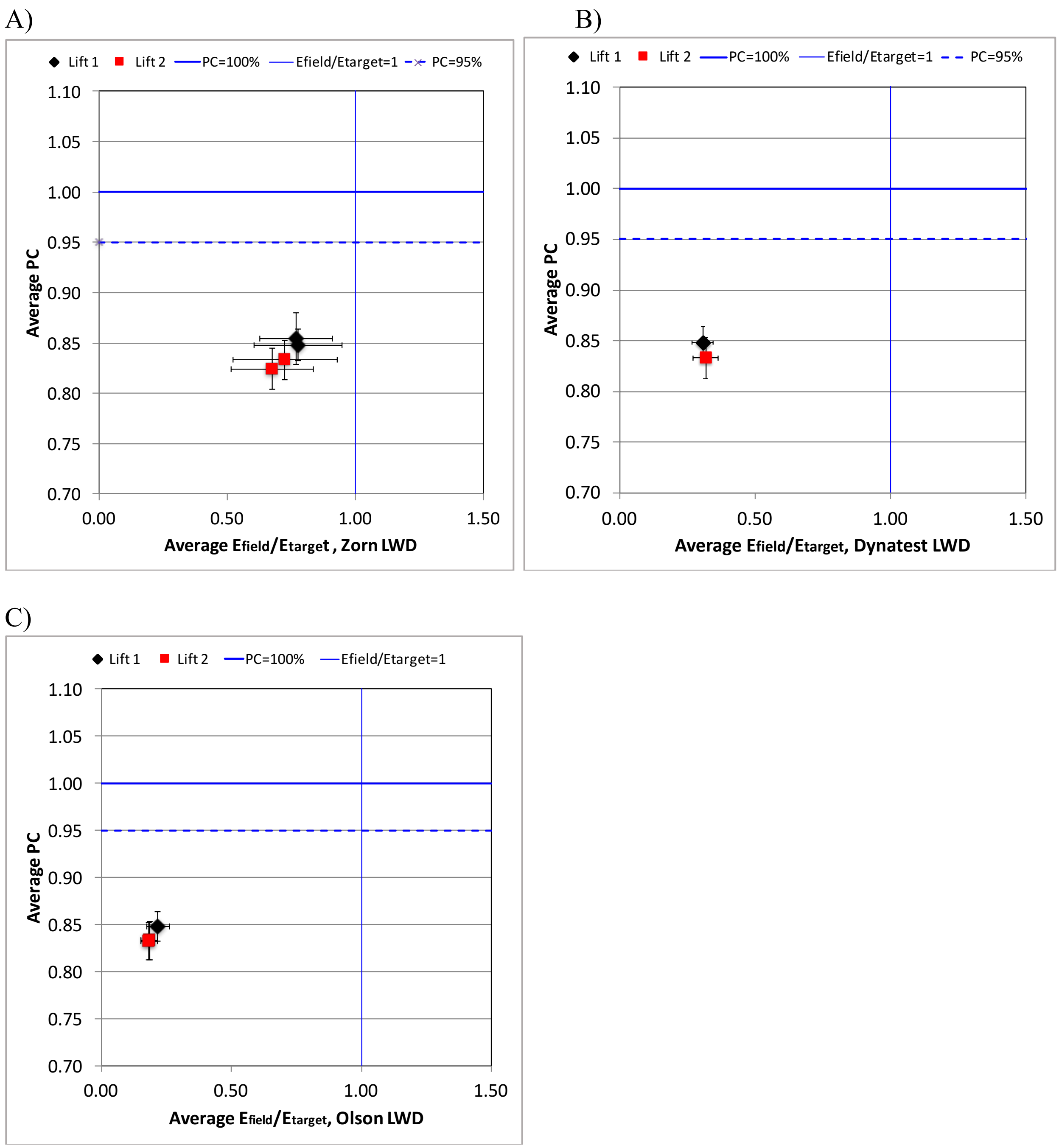



**Figure 36. Average PC versus average $E_{field}$ to $E_{target}$ ratio for NY embankment soil for (A) Zorn, (B) Dynatest, and (C) Olson LWDs**

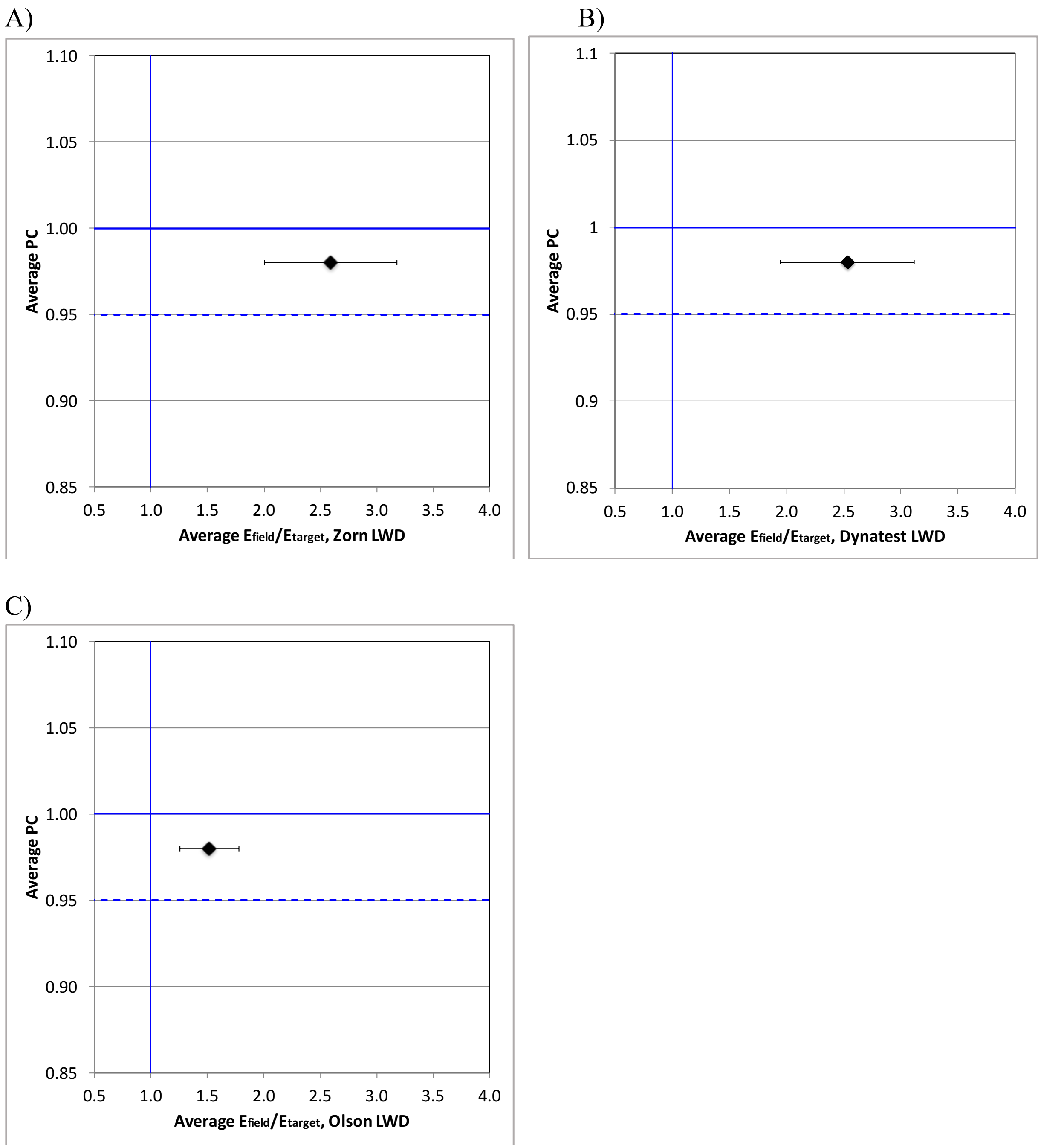



**Figure 37. Average PC versus average $E_{field}$ to $E_{target}$ ratio for MD337 base for (A) Zorn, (B) Dynatest, and (C) Olson LWDs**

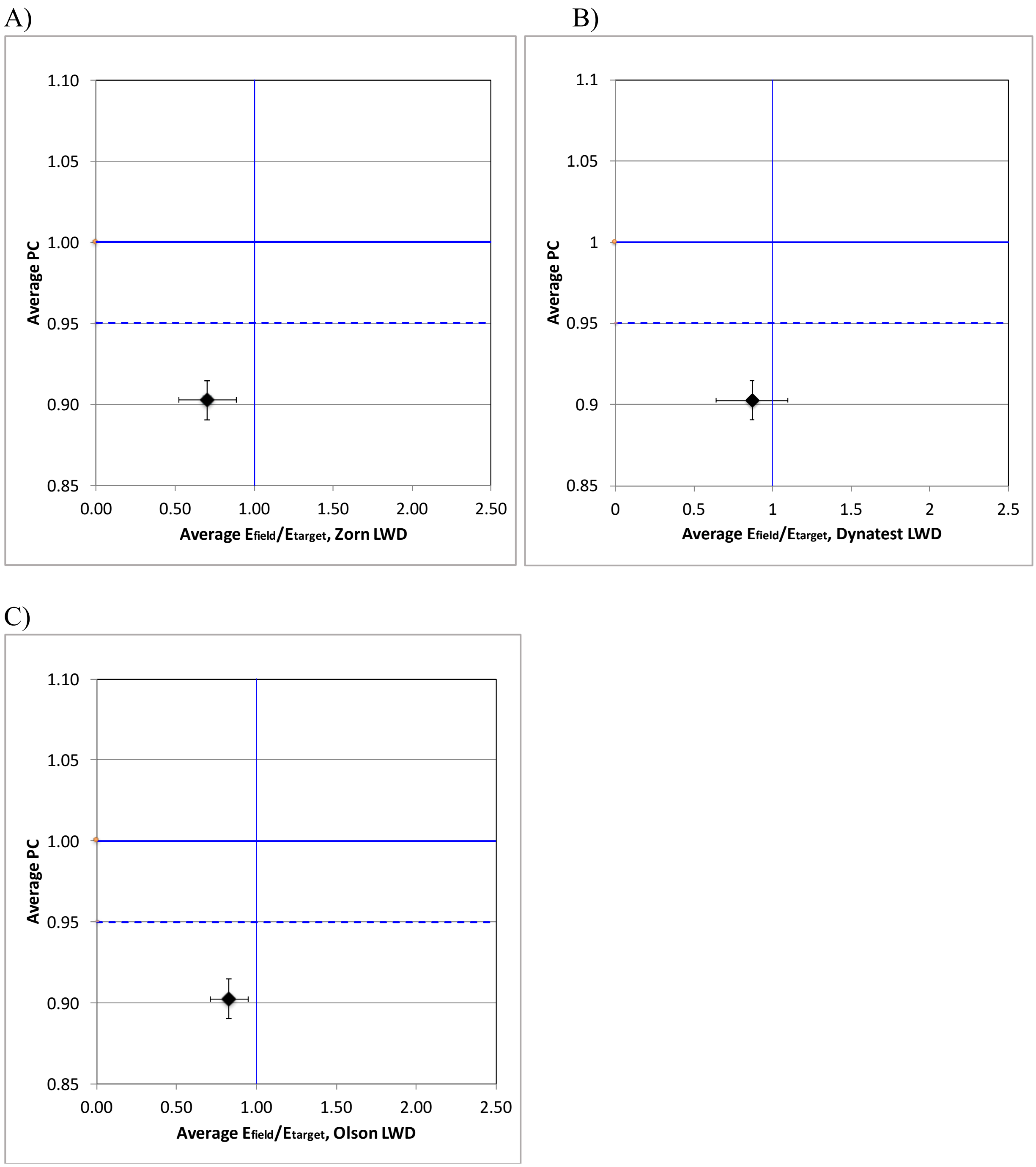
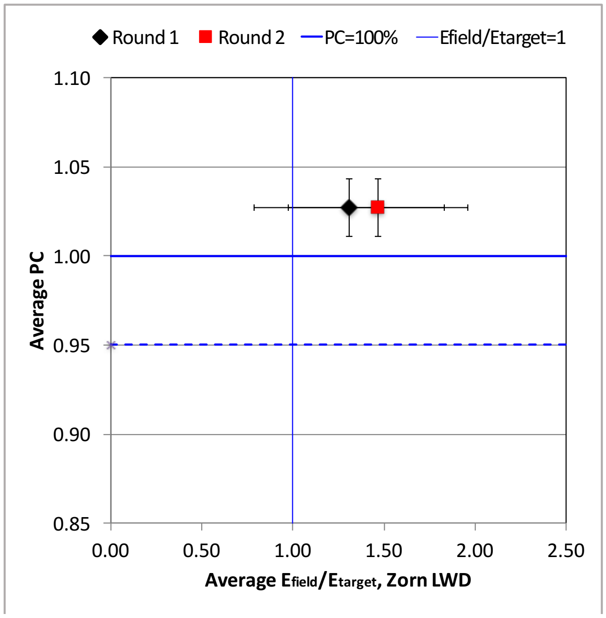



**Figure 38. Average PC versus average $E_{field}$ to corrected $E_{target}$ ratio for MD404 base for (A) Zorn, (B) Dynatest, and (C) Olson LWDs**

A)




B)

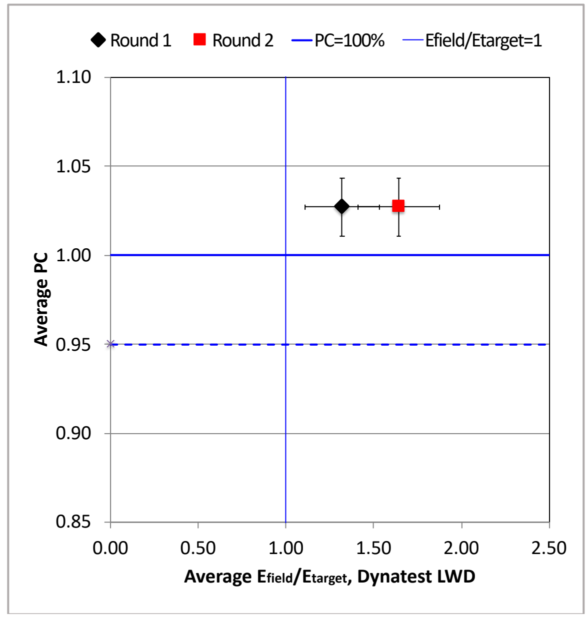



**Figure 39. Average PC versus average $E_{field}$ to corrected $E_{target}$ ratio for FL base for (A) Zorn, (B) Dynatest LWDs**

## 4.5. Effect of compaction imposed by LWD drops

To investigate the effect of additional compaction imposed by LWD drops to the testing spot and repeatability of moduli measurement, testing was performed in the following sequence on each station:

(1) Six drops from half height or a lowered drop height on the designated station: Three seating drops followed by three measurement drops.

(2) Six drops from full height on the same spot as step 1 without moving the LWD plate: Three seating drops followed by three measurement drops.

(3) Six drops from the same half height or a lowered drop as in step 1 on the same spot without moving the LWD plate: Three seating drops followed by three measurement drops.

In this report, moduli measured form step 1 and step 3 are referred to as first half-height drop ($E_{h1}$) and second half-height drop moduli ($E_{h2}$), respectively. The applied load from lower drop height is adjusted based on Equation 11 for the Zorn LWD.

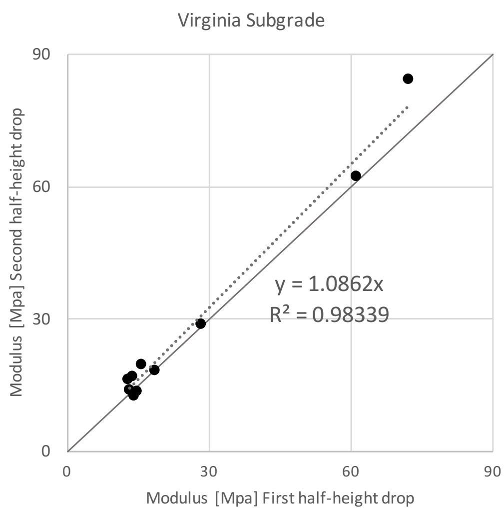
$E_{h1}$ are plotted versus $E_{h2}$ for each LWD in Figure 40 to Figure 42. Correlation equation and coefficient of determination ($R^2$) are shown for each round of testing (R) and compacted lift (L) at each test site.

Table 11 to Table 13 present a summary of the correlation equations (y=ax) and coefficient of determinations ($R^2$) along with average PC for each test site. The PCs for the sites with inadequate compaction are indicated with red font color.

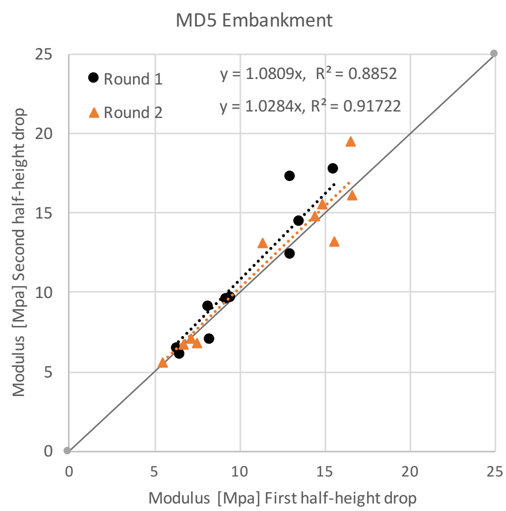
For the Zorn LWD, very good correlation exists between $E_{h1}$ and $E_{h2}$ as expected. Overall, $E_{h2}$ are 2% to 20% more than $E_{h1}$ for well-compacted sites (PC more than 95%). This value will change to above 40% for under-compacted sites such as the NY embankment and FL subgrade materials.

However, the Olson LWD shows a variable $R^2$ in a range of -0.28 to 0.99 depending on the test site. The $E_{h2}$ are 3% to 15% more than $E_{h1}$ for well-compacted sites and to above 15% for under-compacted sites.

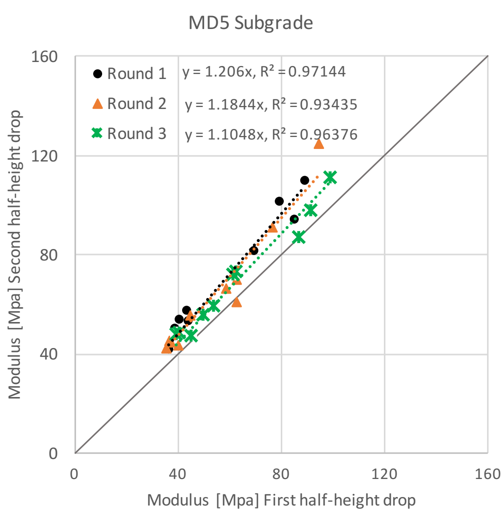
The Dynatest LWD exhibits fairly good correlations for well-compacted soils, while the $R^2$ reduces significantly for under-compacted sites.



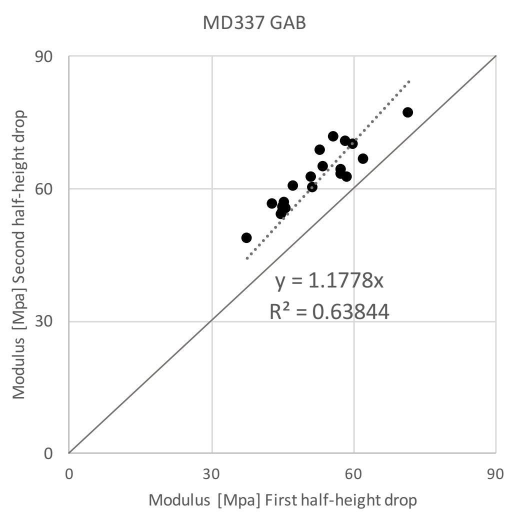
A)



B)



C)



D)

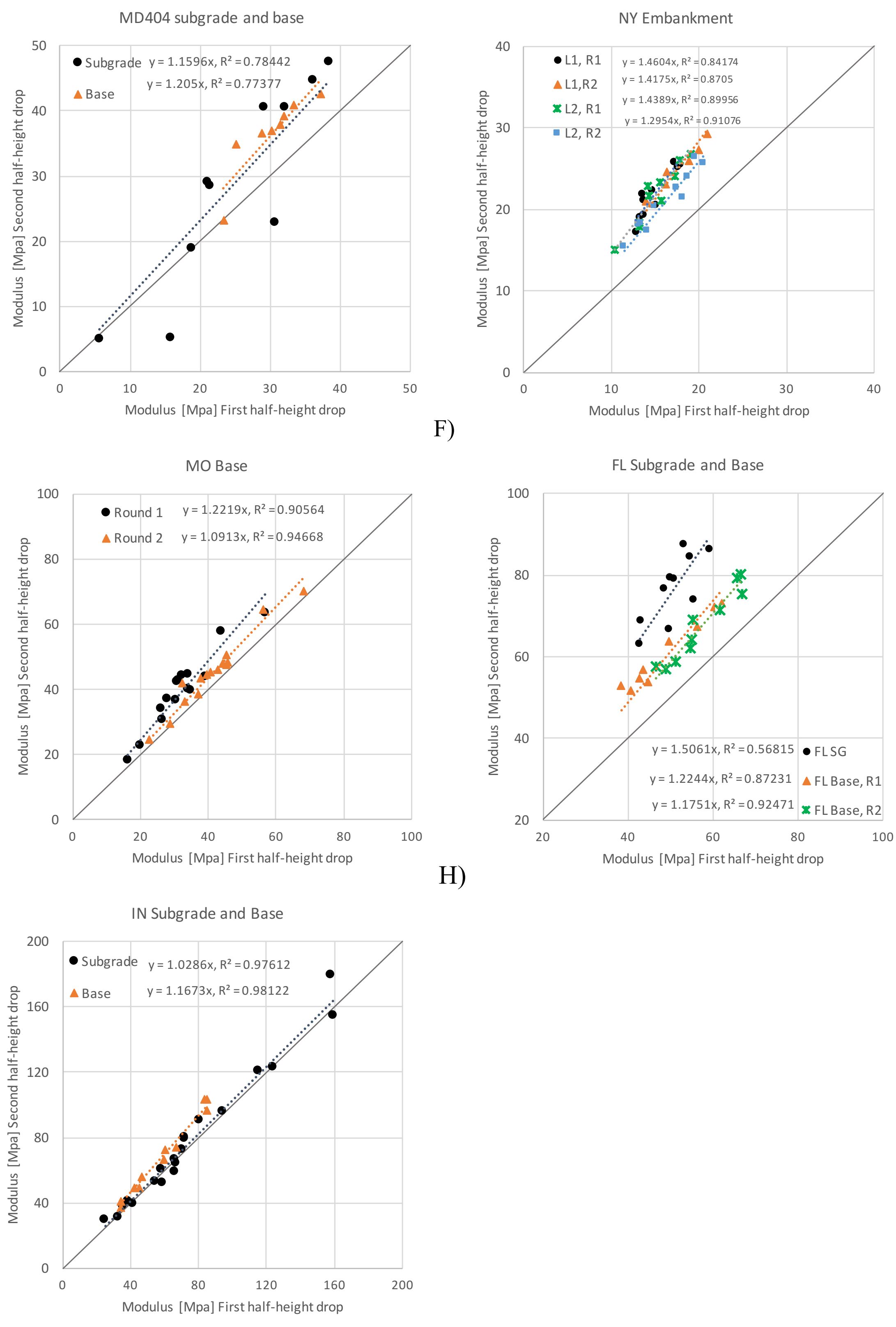
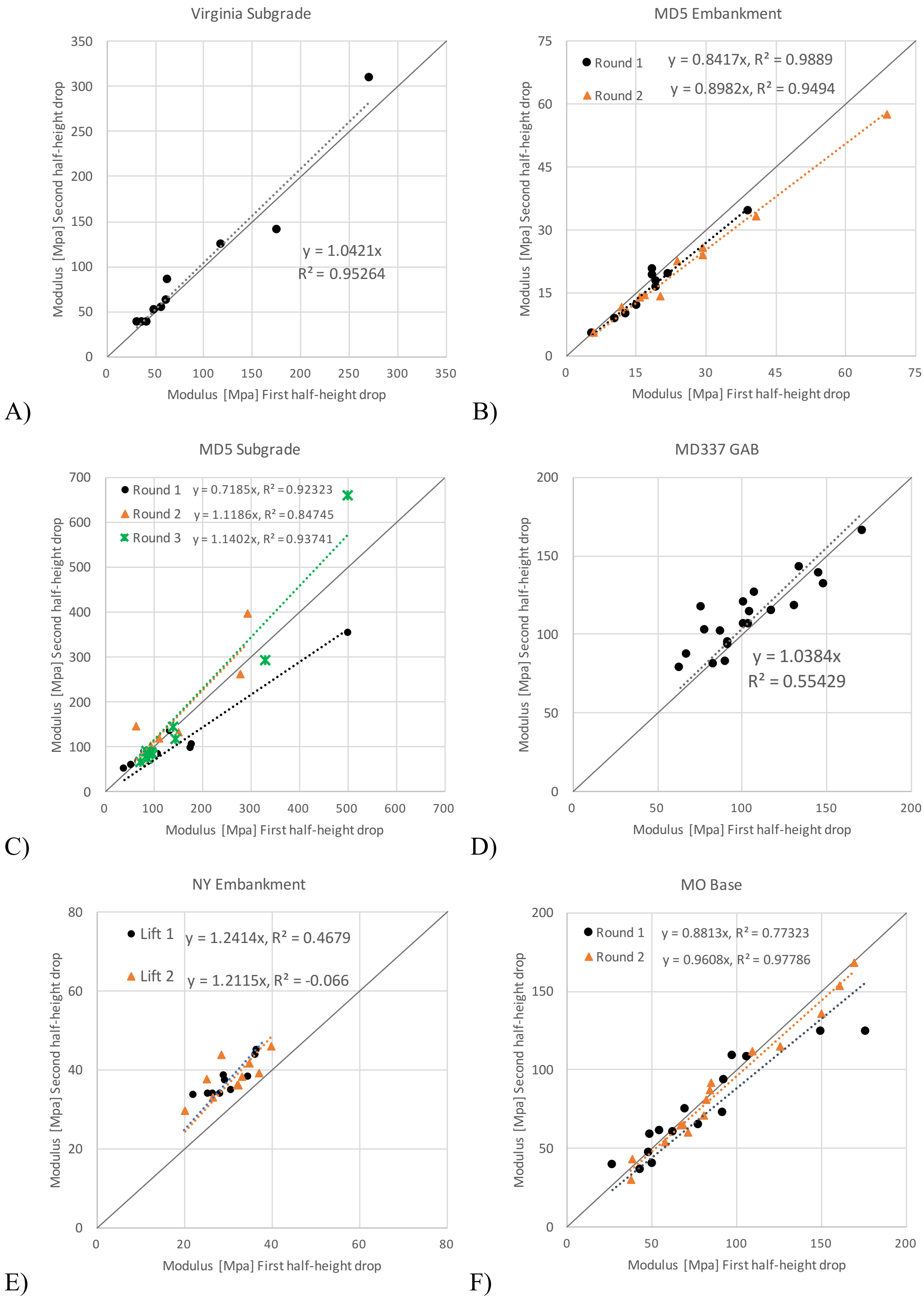
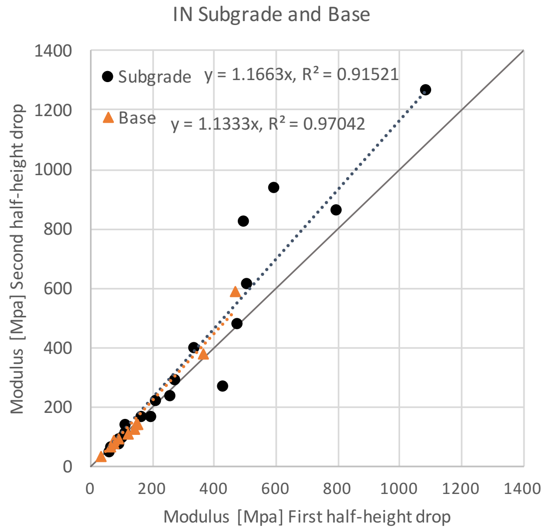
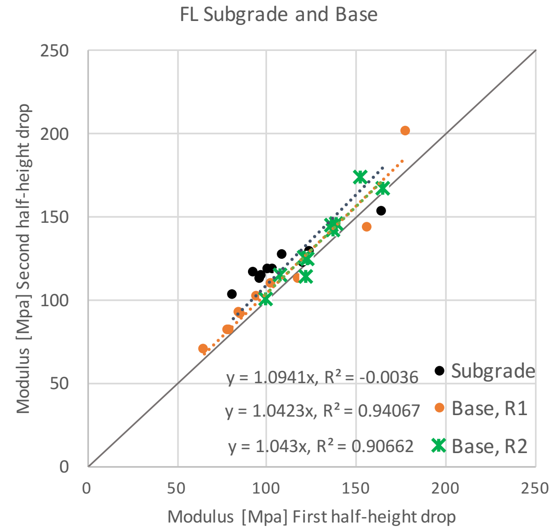



**Figure 40. Comparison of moduli at first half-height drop and moduli at second half-height drop for Zorn LWD**

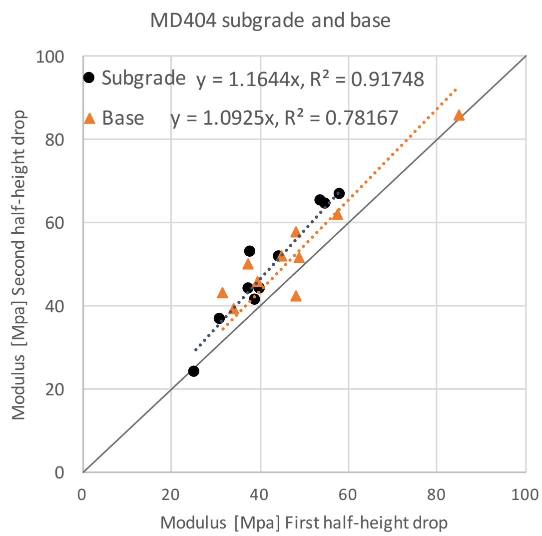

Virginia Subgrade
y = 1.0421x
R² = 0.95264
Modulus [Mpa] Second half-height drop
Modulus [Mpa] First half-height drop
A)
MD5 Embankment
Round 1
Round 2
y = 0.8417x, R² = 0.9889
y = 0.8982x, R² = 0.9494
Modulus [Mpa] Second half-height drop
Modulus [Mpa] First half-height drop
B)
MD5 Subgrade
Round 1 y = 0.7185x, R² = 0.92323
Round 2 y = 1.1186x, R² = 0.84745
Round 3 y = 1.1402x, R² = 0.93741
Modulus [Mpa] Second half-height drop
Modulus [Mpa] First half-height drop
C)
MD337 GAB
y = 1.0384x
R² = 0.55429
Modulus [Mpa] Second half-height drop
Modulus [Mpa] First half-height drop
D)
NY Embankment
Lift 1 y = 1.2414x, R² = 0.4679
Lift 2 y = 1.2115x, R² = -0.066
Modulus [Mpa] Second half-height drop
Modulus [Mpa] First half-height drop
E)
MO Base
Round 1 y = 0.8813x, R² = 0.77323
Round 2 y = 0.9608x, R² = 0.97786
Modulus [Mpa] Second half-height drop
Modulus [Mpa] First half-height drop
F)




G)

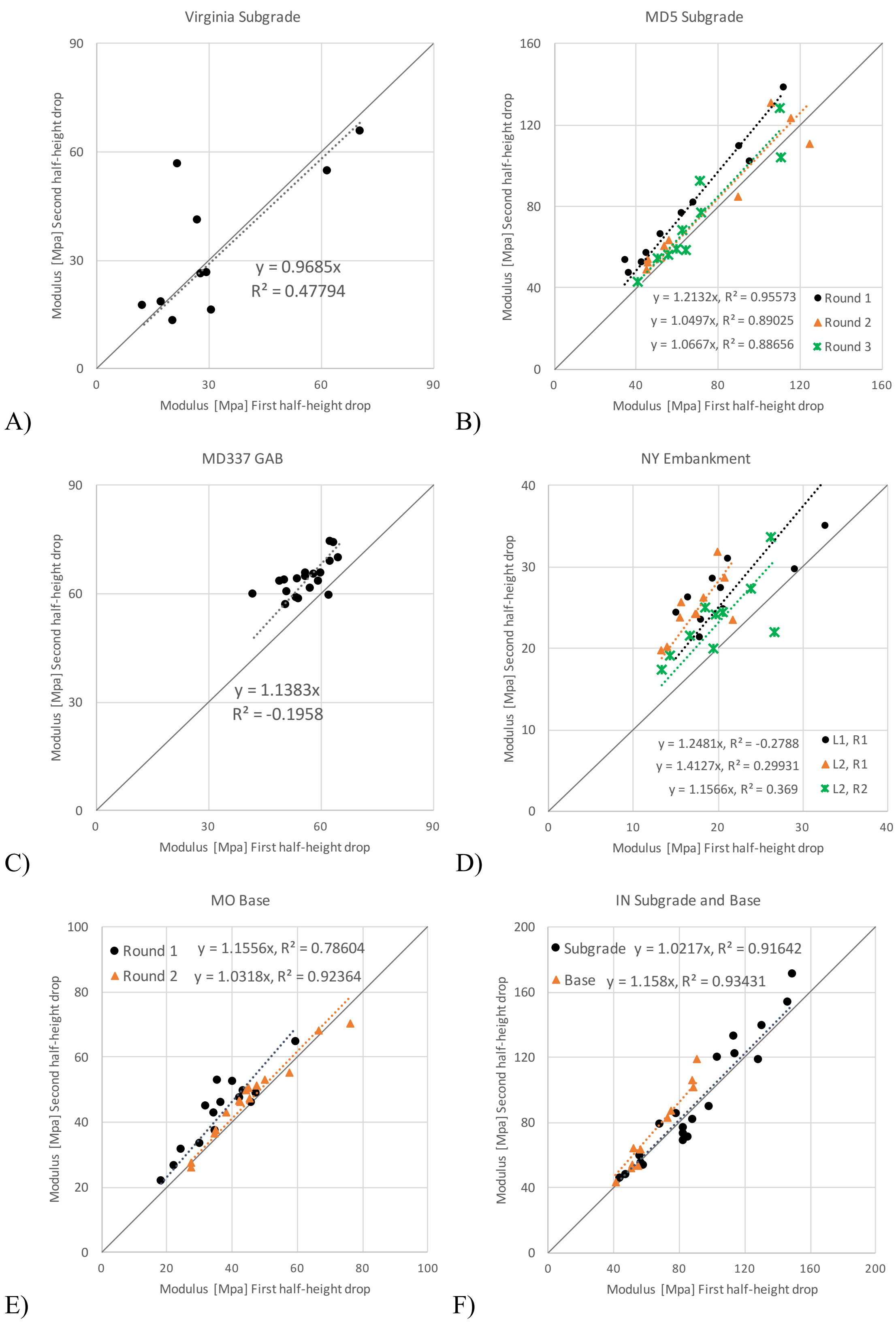


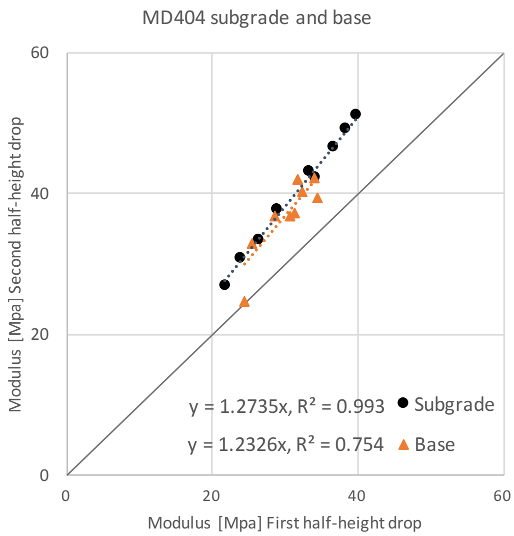

H)




I)

**Figure 41. Comparison of moduli at first half-height drop and moduli at second half-height drop for Dynatest LWD**


Virginia Subgrade
y = 0.9685x
R² = 0.47794
Modulus [Mpa] Second half-height drop
Modulus [Mpa] First half-height drop
A)
MD5 Subgrade
y = 1.2132x, R² = 0.95573
y = 1.0497x, R² = 0.89025
y = 1.0667x, R² = 0.88656
Round 1
Round 2
Round 3
Modulus [Mpa] Second half-height drop
Modulus [Mpa] First half-height drop
B)
MD337 GAB
y = 1.1383x
R² = -0.1958
Modulus [Mpa] Second half-height drop
Modulus [Mpa] First half-height drop
C)
NY Embankment
y = 1.2481x, R² = -0.2788
y = 1.4127x, R² = 0.29931
y = 1.1566x, R² = 0.369
L1, R1
L2, R1
L2, R2
Modulus [Mpa] Second half-height drop
Modulus [Mpa] First half-height drop
D)
MO Base
Round 1 y = 1.1556x, R² = 0.78604
Round 2 y = 1.0318x, R² = 0.92364
Modulus [Mpa] Second half-height drop
Modulus [Mpa] First half-height drop
E)
IN Subgrade and Base
Subgrade y = 1.0217x, R² = 0.91642
Base y = 1.158x, R² = 0.93431
Modulus [Mpa] Second half-height drop
Modulus [Mpa] First half-height drop
F)




G)

**Figure 42. Comparison of moduli at first half-height drop and moduli at second half-height drop for Olson LWD**

**Table 11. Corrlation between moduli at second half-height drop and moduli at first half-height drop for Zorn LWD**

| Location and Soil Type | Round of Testing | Correlation (intercept=0) | R2 | Average %PC |
|---|---|---|---|---|
| Virginia, Phenix subgrade | 1st | y = 1.0862x | 0.983 | 96.8 |
| MD 5 waste contaminated embankment | 1st | y = 1.0809x | 0.885 | 97.9 |
| | 2nd | y = 1.0284x | 0.917 | 98.3 |
| MD 5 subgrade | 1st | y = 1.206x | 0.971 | 98.6 |
| | 2nd | y = 1.1844x | 0.934 | 98.4 |
| | 3rd | y = 1.1048x | 0.964 | 98.8 |
| MD 337, deep GAB layer | 1st | y = 1.1778x | 0.638 | 98.0 |
| MD 404 subgrade | 1st | y = 1.1596x | 0.784 | N/A |
| MD 404 GAB | 1st | y = 1.205x | 0.774 | 90.2 |
| New York, embankment (local subgrade) | Lift 1, 1st | y = 1.4604x | 0.842 | 84.8 |
| | Lift 1, 2st | y = 1.4175x | 0.871 | 85.4 |
| | Lift 2, 1st | y = 1.4389x | 0.900 | 83.2 |
| | Lift 2, 2nd | y = 1.2954x | 0.911 | 83.2 |
| Indiana, cement modified subgrade | 1st | y = 1.0286x | 0.976 | N/A |
| Indiana, GAB | 1st | y = 1.1673x | 0.981 | N/A |
| Missouri, GAB | 1st | y = 1.2219x | 0.906 | 100.0 |
| | 2nd | y = 1.0913x | 0.947 | 99.5 |
| Florida, Subgrade | 1st | y = 1.5061x | 0.568 | 90.8 |
| Florida, Base | 1st | y = 1.2244x | 0.872 | 102.7 |
| | 2nd | y = 1.1751x | 0.925 | 102.4 |

**Table 12. Corrlation between moduli at second half-height drop and moduli at first half-height drop for Olson LWD**

| Location and Soil Type | Round of Testing | Correlation (intercept=0) | R2 | Average %PC |
|---|---|---|---|---|
| Virginia, Phenix subgrade | 1st | y = 0.9685x | 0.478 | 96.8 |
| MD 5 subgrade | 1st | y = 1.2132x | 0.956 | 98.6 |
| | 2nd | y = 1.0497x | 0.890 | 98.4 |
| | 3rd | y = 1.0667x | 0.887 | 98.8 |
| MD 337, deep GAB layer | 1st | y = 1.1383x | -0.196 | 98.0 |
| MD 404 subgrade | 1st | y = 1.2735x | 0.993 | N/A |
| MD 404 GAB | 1st | y = 1.2326x | 0.755 | 90.2 |
| New York, embankment (local subgrade) | Lift 1, 1st | y = 1.2481x | -0.279 | 84.8 |
| | Lift 2, 1st | y = 1.4127x | 0.299 | 83.2 |
| | Lift 2, 2st | y = 1.1566x | 0.369 | 83.2 |
| Indiana, cement modified subgrade | 1st | y = 1.0217x | 0.916 | N/A |
| Indiana, GAB | 1st | y = 1.158x | 0.934 | N/A |
| Missouri, GAB | 1st | y = 1.1556x | 0.786 | 100.0 |
| | 2nd | y = 1.0318x | 0.924 | 99.5 |

**Table 13. Corrlation between moduli at second half-height drop and moduli at first half-height drop for Dynatest LWD**

| Location and Soil Type | Round of Testing | Correlation (intercept=0) | R2 | Average %PC |
|---|---|---|---|---|
| Virginia, Phenix subgrade | 1st | y = 1.0421x | 0.953 | 96.8 |
| MD 5 waste contaminated embankment | 1st | y = 0.8982x | 0.949 | 97.9 |
| | 2nd | y = 0.8417x | 0.989 | 98.3 |
| MD 5 subgrade | 1st | y = 0.7185x | 0.923 | 98.6 |
| | 2nd | y = 1.1186x | 0.847 | 98.4 |
| | 3rd | y = 1.1402x | 0.937 | 98.8 |
| MD 337, deep GAB layer | 1st | y = 1.0384x | 0.554 | 98.0 |
| MD 404 subgrade | 1st | y = 1.1644x | 0.917 | N/A |
| MD 404 GAB | 1st | y = 1.0925x | 0.782 | 90.2 |
| New York, embankment (local subgrade) | Lift 1, 1st | y = 1.2414x | 0.468 | 84.8 |
| | Lift 2, 1st | y = 1.2115x | -0.066 | 83.2 |
| Indiana, cement modified subgrade | 1st | y = 1.1663x | 0.915 | N/A |
| Indiana, GAB | 1st | y = 1.1333x | 0.970 | N/A |
| Missouri, GAB | 1st | y = 0.8813x | 0.773 | 100.0 |
| | 2nd | y = 0.9608x | 0.978 | 99.5 |
| Florida, Subgrade | 1st | y = 1.0941x | -0.004 | 90.8 |
| Florida, Base | 1st | y = 1.0423x | 0.941 | 102.7 |
| | 2nd | y = 1.043x | 0.907 | 102.4 |

# 5. Chapter 5: Specification Development

The research findings were summarized in two modulus-based QA procedures suitable for implementation by state DOTs and engineers. The specifications are prepared in AASHTO format, which is familiar to the construction community and highway agencies (Appendix A). The goals of the test specifications were to be reasonably easy to implement and to not increase field workload significantly. The specifications were written broadly at the end of the pooled fund study so that each agency can tailor them to meet their local needs.

Establishing appropriate acceptance limits is an important step. Both engineering requirements and economic consequences should be contemplated when determining acceptance limits.

In order to find the threshold of acceptable field to target moduli ratios, material with passing and failing compaction are graphed versus $E_{field}/E_{target}$ for each LWD in Figure 43.

A field to target modulus ratio of 1 can be selected as the threshold to separate the under-compacted sites from the well-compacted soils for all three LWDs.

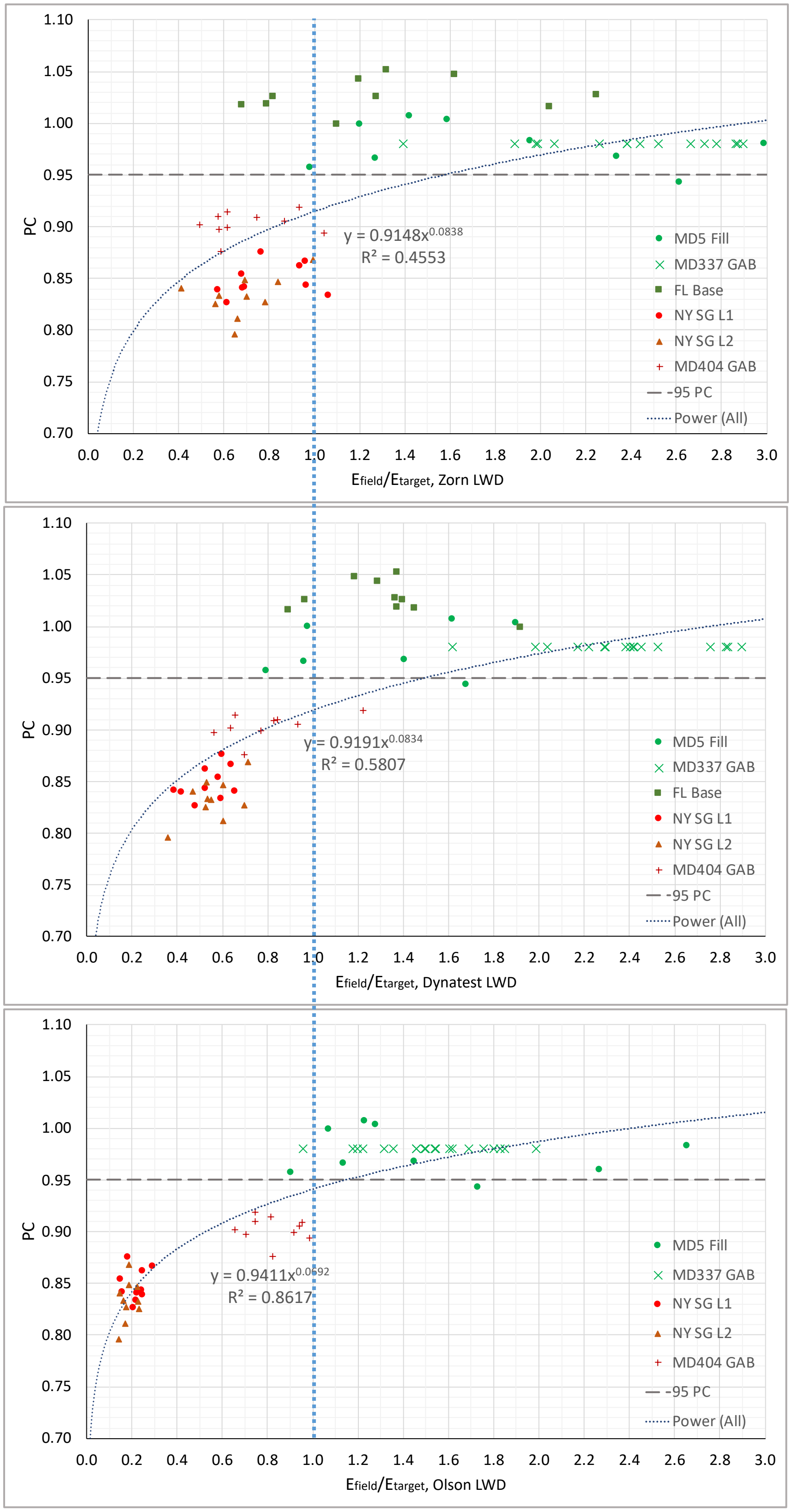
A)
B)
C)



**Figure 43. Lower specification limit for $E_{field}$ /$E_{target}$ for (A) Zorn, (B) Dynatest, and (C) Olson LWDs**

Material should be rejected when a considerable number of field QA tests produce modulus ratios outside the acceptable limit. This can be implemented using the percentage within specification limit (PWL) methodology in AASHTO R 9-05 based on the quality index Q (AASHTO R 9-05):

**Equation 12**

$$Q = \frac{\overline{X} - LSL}{S}$$

$\overline{X}$ = sample mean for the lot/sublot,

LSL = lower specification limit, and

s = sample standard deviation for the lot/sublot.

Then the required PWL can be obtained from the PWL estimation table for the required Q value and given target sample size.

Table 14 shows an example table for relating the Q value with the PWL for a sample size of 10. A complete set of PWL tables for samples size of 3 to 30 are available in the *Quality Assurance Software for the Personal Computer* (1996).

Appropriate remedial procedures should be adopted for lots with an estimated PWL less than the agency minimum. Removal and replacement, corrective action, or reduced pay factor are common remedial procedures.

**Table 14. A PWL estimation table for a sample size of 10 (from the *Quality Assurance Software for the Personal Computer*, 1996)**

PERCENT WITHIN LIMITS ESTIMATION TABLE

VARIABILITY-UNKNOWN PROCEDURE — SAMPLE SIZE 10 — STANDARD DEVIATION METHOD

| Q | 0.00 | 0.01 | 0.02 | 0.03 | 0.04 | 0.05 | 0.06 | 0.07 | 0.08 | 0.09 |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.0 | 50.00 | 50.38 | 50.77 | 51.15 | 51.54 | 51.92 | 52.30 | 52.69 | 53.07 | 53.46 |
| 0.1 | 53.84 | 54.22 | 54.60 | 54.99 | 55.37 | 55.75 | 56.13 | 56.51 | 56.89 | 57.27 |
| 0.2 | 57.65 | 58.03 | 58.40 | 58.78 | 59.16 | 59.53 | 59.91 | 60.28 | 60.66 | 61.03 |
| 0.3 | 61.40 | 61.77 | 62.14 | 62.51 | 62.88 | 63.25 | 63.62 | 63.98 | 64.35 | 64.71 |
| 0.4 | 65.07 | 65.43 | 65.79 | 66.15 | 66.51 | 66.87 | 67.22 | 67.58 | 67.93 | 68.28 |
| 0.5 | 68.63 | 68.98 | 69.33 | 69.68 | 70.02 | 70.36 | 70.71 | 71.05 | 71.39 | 71.72 |
| 0.6 | 72.06 | 72.40 | 72.73 | 73.06 | 73.39 | 73.72 | 74.04 | 74.37 | 74.69 | 75.01 |
| 0.7 | 75.33 | 75.65 | 75.97 | 76.28 | 76.59 | 76.90 | 77.21 | 77.52 | 77.82 | 78.13 |
| 0.8 | 78.43 | 78.73 | 79.02 | 79.32 | 79.61 | 79.90 | 80.19 | 80.48 | 80.77 | 81.05 |
| 0.9 | 81.33 | 81.61 | 81.89 | 82.16 | 82.44 | 82.71 | 82.97 | 83.24 | 83.51 | 83.77 |
| 1.0 | 84.03 | 84.28 | 84.54 | 84.79 | 85.04 | 85.29 | 85.54 | 85.78 | 86.03 | 86.27 |
| 1.1 | 86.50 | 86.74 | 86.97 | 87.20 | 87.43 | 87.66 | 87.88 | 88.10 | 88.32 | 88.54 |
| 1.2 | 88.76 | 88.97 | 89.18 | 89.39 | 89.59 | 89.79 | 90.00 | 90.19 | 90.39 | 90.58 |
| 1.3 | 90.78 | 90.97 | 91.15 | 91.34 | 91.52 | 91.70 | 91.88 | 92.05 | 92.23 | 92.40 |
| 1.4 | 92.56 | 92.73 | 92.90 | 93.06 | 93.22 | 93.37 | 93.53 | 93.68 | 93.83 | 93.98 |
| 1.5 | 94.13 | 94.27 | 94.41 | 94.55 | 94.69 | 94.82 | 94.95 | 95.08 | 95.21 | 95.34 |
| 1.6 | 95.46 | 95.59 | 95.70 | 95.82 | 95.94 | 96.05 | 96.16 | 96.27 | 96.38 | 96.48 |
| 1.7 | 96.59 | 96.69 | 96.79 | 96.89 | 96.98 | 97.07 | 97.17 | 97.26 | 97.34 | 97.43 |
| 1.8 | 97.51 | 97.60 | 97.68 | 97.75 | 97.83 | 97.91 | 97.98 | 98.05 | 98.12 | 98.19 |
| 1.9 | 98.25 | 98.32 | 98.38 | 98.44 | 98.50 | 98.56 | 98.62 | 98.67 | 98.73 | 98.78 |
| 2.0 | 98.83 | 98.88 | 98.93 | 98.97 | 99.02 | 99.06 | 99.10 | 99.14 | 99.18 | 99.22 |
| 2.1 | 99.26 | 99.29 | 99.33 | 99.36 | 99.39 | 99.42 | 99.45 | 99.48 | 99.51 | 99.54 |
| 2.2 | 99.56 | 99.59 | 99.61 | 99.63 | 99.66 | 99.68 | 99.70 | 99.71 | 99.73 | 99.75 |
| 2.3 | 99.77 | 99.78 | 99.80 | 99.81 | 99.82 | 99.84 | 99.85 | 99.86 | 99.87 | 99.88 |
| 2.4 | 99.89 | 99.90 | 99.91 | 99.92 | 99.92 | 99.93 | 99.94 | 99.94 | 99.95 | 99.95 |
| 2.5 | 99.96 | 99.96 | 99.97 | 99.97 | 99.97 | 99.98 | 99.98 | 99.98 | 99.99 | 99.99 |
| 2.6 | 99.99 | 99.99 | 99.99 | 99.99 | 99.99 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |

VALUES IN BODY OF TABLE ARE ESTIMATES OF PERCENT WITHIN LIMITS CORRESPONDING TO SPECIFIC VALUES OF Q = (AVERAGE - LOWER LIMIT) / (STANDARD DEVIATION) OR Q = (UPPER LIMIT - AVERAGE) / (STANDARD DEVIATION). FOR NEGATIVE Q VALUES, THE TABLE VALUES MUST BE SUBTRACTED FROM 100.

Traditional methods of density-based compaction QA requires a minimum number of density tests performed on the compacted layer to insure adequate compaction. For instance, MDOT SHA requires performing moisture density test (NDG or sand cone) at a rate of 4 tests per lane mile per lift (from MD *Material Quality Assurance Process, Soil and Aggregate Division*).

In order to establish the minimum required LWD testing in the field, a preliminary variability analysis was performed for the devices in this study. The allowable error was matched to the NDG error based on the standard deviation data captured in the field verification phase.

Since sample sizes were small and the population standard deviation is unknown, a t-distribution parameter was used to calculate the minimum sample size (n) from Equation 13 for each LWD:

**Equation 13**

$$n = \left(\frac{t.\,s}{e}\right)^2$$

s = sample standard deviation,

t= value from t-table for each confidence level and degree of freedom,

e= acceptable error.

The average standard deviation of PC measured by NDG in the field was about 2.5 for the material in this study. For 4 tests and a 95% confidence level, the required t value equals 2.353. Then acceptable error e can be calculated:

$$e = \frac{t.s}{\sqrt{n}} = \frac{2.353 \times 2.5}{\sqrt{4}} = 2.941 \cong 3$$

Table 15 and Table 16 present the results per lane mile per lift, based on the minimum, maximum, and average standard deviations measured in this study.

**Table 15. Variabily analysis to find the minimum number of tests in the field for subgrade material**

| | | 80% | | | 90% | | | 95% | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Parameter** | **Min.** | **Max.** | **Avg.** | **Min.** | **Max.** | **Avg.** | **Min.** | **Max.** | **Avg.** |
| **Zorn LWD** | s [MPa] | 2.75 | 25.80 | 11.50 | 2.75 | 25.80 | 11.50 | 2.75 | 25.80 | 11.50 |
| | n | 1 | 55 | 11 | 2 | 125 | 25 | 4 | - | 43 |
| **Dynatest LWD** | s [MPa] | 4.54 | 134.76 | 50.68 | 4.54 | 134.76 | 50.68 | 4.54 | 134.76 | 50.68 |
| | n | 2 | - | 250 | 4 | - | - | 9 | - | - |
| **Olson LWD** | s [MPa] | 2.99 | 36.18 | 14.77 | 2.99 | 36.18 | 14.77 | 2.99 | 36.18 | 14.77 |
| | n | 1 | 100 | 18 | 2 | - | 40 | 4 | - | 65 |

**Table 16. Variabily analysis to find the minimum number of tests in the field for base material**

| | | 80% | | | 90% | | | 95% | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Parameter** | **Min.** | **Max.** | **Avg.** | **Min.** | **Max.** | **Avg.** | **Min.** | **Max.** | **Avg.** |
| **Zorn LWD** | s [MPa] | 5.52 | 12.51 | 9.52 | 5.52 | 12.51 | 9.52 | 5.52 | 12.51 | 9.52 |
| | n | 3 | 13 | 8 | 7 | 30 | 18 | 11 | 50 | 31 |
| **Dynatest LWD** | s [MPa] | 9.73 | 37.08 | 23.37 | 9.73 | 37.08 | 23.37 | 9.73 | 37.08 | 23.37 |
| | n | 9 | 110 | 45 | 19 | - | 104 | 30 | - | - |
| **Olson LWD** | s [MPa] | 5.23 | 16.29 | 10.76 | 5.23 | 16.29 | 10.76 | 5.23 | 16.29 | 10.76 |
| | n | 3 | 22 | 10 | 6 | 50 | 23 | 10 | 85 | 40 |

Agencies are encouraged to calculate the minimum required testing based on the modulus standard deviation data for their materials and their selected LWD device type(s). Additional testing may also be required if deemed necessary by the inspector.

To assure that LWD testing is performed over the entire lot and not concentrated in one area, stratified random sampling using random locations within sublots is recommended according to ASTM D 3665-122.

At the end of the TPF-5(285) pooled fund study it was recommended that interested state DOTs and agencies implement a local calibration procedure to find the lower specification limit (LSL) for $E_{field}/E_{target}$ for their local materials.

The following steps can be taken:

(1) Determine the $E_{target}$ by performing LWD on mold test in the laboratory.

(2) Measure $E_{field}$ after a few passes of the compactor and before achieving MDD (i.e., under-compacted condition).

(3) Measure $E_{field}$ after achieving MDD (i.e., well-compacted condition).

(4) Calculate the $E_{field}$ /$E_{target}$ for both passing and failing conditions.

(5) Find the threshold which separates the field to target ratio for passing and failing condition.

MDOT SHA, which was the leading agency for the pooled fund study funded, conducted a follow up project starting Fall 2017 to December 2018 to calibrate the specification procedure for the geomaterial in the state of Maryland.

# 6. Chapter 6: Implementation and Pilot Projects

Maryland Department of Transportation State Highway Administration (MDOT SHA) is responsible for assuring the quality of the geomaterials produced, placed, and compacted for road foundations and embankment construction in the state of Maryland. The Office of Material Technology (OMT) performs field inspection to verify that the quality of the materials and construction fall within the acceptance specifications (Goulias & Karimi, 2013).

The two implementation-ready specifications developed during the pooled fund study were deliberately kept general to allow tailoring and calibration by DOTs for their local soil types and construction practices. MDOT SHA funded a study with the goal of providing a transition between density to modulus-based QA based on the developed specifications for geomaterials in the state of Maryland.

Acceptable compaction quality is achieved when the percent compaction (PC) of a layer is above the MDOT SHA's acceptable density limit at that depth and/or is deemed satisfactory by the field inspectors. Failing compaction quality is defined as failure to meet the MDOT SHA's MC or PC criteria and/or is judged as poor quality by field inspectors.

The modulus of geomaterials is significantly dependent on MC (Pacheco & Nazarian, 2011). Therefore, the QA methodology should restrict the compaction MC to the MDOT SHA's acceptable limits and base the target modulus for those MC limits. This chapter also provides recommendations for more uniform construction to reduce variability of unbound material properties in the field.

Replacing NDGs with LWDs and portable MC measurement devices is estimated to save approximately $50K per year in operating costs (calibration, maintenance, radiation safety, secure storage) for MDOT SHA.

The primary objective of the MDOT SHA follow-on study was to rigorously validate the TPF-5(285) methodology for Maryland unbound materials. For this purpose: (1) a range of geomaterials commonly used for road base and embankment construction were tested; (2) the repeatability of LWD moduli on mold values were assessed; and (3) LWD testing in the field was performed concurrent with NDG measurements to compare modulus- vs. density-based compaction QA.

The secondary objectives of the study included: (1) determining the minimum required LWD testing and data collection in the field based on the typical standard deviation of field modulus values, (2) establishing appropriate acceptance criteria and lower specification limits for a percent-within-limits QA approach, and (3) forming a catalog of target moduli for unbound materials commonly used in Maryland.

To address the objectives, the research team held several meetings with MDOT SHA engineers from the Soils and Aggregates Technology Division to identify the types of materials, available construction projects, and laboratory testing techniques to include in the study in order to refine the proposed research tasks. The effort was structured into the following tasks and subtasks:

***Task 1- Equipment selection***

The most practical MC measurement device, NDG, and LWD type were selected based on research team’s experience and in consultation with OMT.

***Task 2- Controlled field test***

LWD and NDG testing was performed on a variety of projects during the Fall 2017 to Fall 2018 construction seasons.

***Task 3- Soil characterization and LWD on mold testing in the lab***

The aggregate gradation and LWD modulus on mold testing were performed for all the materials. Then the field-to-target modulus ratios were established.

***Task 4- Specification refinement***

The target modulus determination, acceptance criteria, and testing frequency were refined in this task based on the testing performed in Tasks 2 and 3.

***Task 5- Final report and meeting***

A final meeting, presentation, and hands on workshop were held in Fall 2018 to transfer the testing technique and experience to OMT engineers.

Based on the evaluation of available categories of LWD devices performed during the pooled fund study and in consultation with MDOT SHA, the Dynatest 3031 LWD was selected. The Ohaus MB45 Moisture Analyzer was also employed for rapid MC measurement in the field.

The conventional density-based compaction evaluation was performed using a Troxler NDG, and for a few test sites using a Troxler EGauge 4590 as well. MDOT SHA personnel performed all NDG and EGauge testing.

## 6.1. Test sites and material

Figure 44 shows the geographic distribution of the projects and aggregate production plants in the state of Maryland. The location number corresponds to the row number in Table 17.

Table 17 summarizes the field projects and visitation dates as well as the material types tested and aggregate sources. A total of nine projects were visited during this study, with 3 additional graded aggregate base (GAB) samples obtained directly from the aggregate production plants.

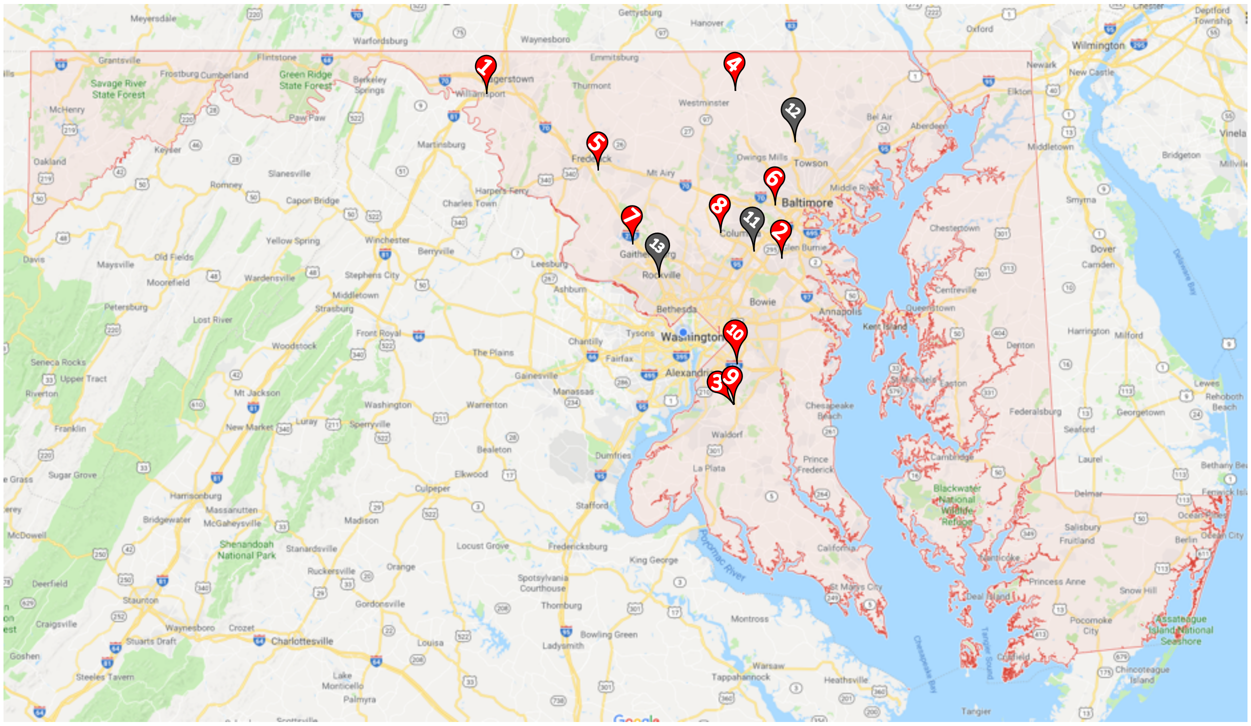



**Figure 44. Location of field projects visited and aggregate quarries in the state of Maryland**

Due to the circumstances and schedule of the projects available during this phase, most of the material tested were GABs. GAB compaction in Maryland is required to achieve 97% of maximum dry density (MDD) as determined by the AASHTO T-180 specification for the final 2 ft lifts. Two types of common borrow fill material were also characterized in this study.

**Table 17. List of field projects and GAB samples from quarries tested**

| # | Project | Contract number | Date visited | Tested material | Device Types | GAB Source |
|---|---|---|---|---|---|---|
| 1 | I-81 widening and super structure (I-81 and MD 63) | WA3445272 | 11/28/17 | GAB | LWD, NDG | Martin Marietta Materials, Pinesburg |
| 2 | Six lane divided reconstruction on MD 175 from west of Reece road to east of Disney Road | AA4365471 | 10/23/17, 10/25/17 | SG, GAB | LWD, NDG | Savage Stone, Laurel |
| 3 | MD 5 ramp at Brandywine road (MD 373/MD 381) roundabout construction | PG1755170 | 10/18/17 | SG, GAB | LWD, NDG | Aggregate Industries, Bladensburg |
| 4 | Geometric improvement MD 482 at Gorsuch and Cape Horn road | CL4515130 | 10/19/17 | Fill | LWD, NDG | Common Borrow, CJ Miller, Finksburg |
| 5 | Replacement Bridge No. 1008400 on MD355 in Fredrick County | FR5595180 | 5/1/18 | SG, GAB | LWD, NDG, Egauge | Common Borrow, Hale Type, source unknown |
| 6 | Multi lane construction on I-695 from MD 144 to south of US 40 | BA7275172 | 5/3/18 | SG, GAB | LWD, NDG, Egauge | Martin Marietta Materials, Texas |
| 7 | I 270 at Watkins Mill road, MD 124 to Great Seneca Creed crossing- Interchange construction | MO3515172R | 5/4/18 | Fill | LWD, NDG, Egauge | Common Borrow, source unknown |
| 8 | MD 32 widening from MD 108 to Linden Church Road | HO1415170 | 6/5/2018, 6/6/2018 | GAB | LWD, NDG, Egauge, Ohaus | Vulcan Materials Company, Fredrick |
| 9 | MD 5 Interchange at Brandywine road (MD 373/MD 381)-interchange construction | PG1755170 | 6/7/18 | GAB | LWD, NDG, Egauge, Ohaus | Aggregate Industries, Bladensburg |
| 10 | I 95 Bridge over Suitland road- Bridge replacement | PG6985180 | 6/12/18 | Fill, GAB | LWD, NDG, Ohaus | Aggregate Industries, Rockville |
| 11 | GAB sample: Savage Stone, Laurel | | | GAB | | |
| 12 | GAB sample: Martin Marietta, Texas Quarry | | | GAB | | |
| 13 | GAB sample: Aggregate Industries, Rockville Quarry | | | GAB | | |

Table 18 presents the gradation for the GAB material used for the visited projects. The sieve analysis results in the table and Figure 45 are the most recent values for the JMF as reported by the MDOT SHA's Soil and Aggregate Division.

According to the MDOT SHA's Aggregate Bulletin, the percent passing from each standard sieve shall fall within an acceptable range that is determined by the %Tolerance (Table 18) for GABs.

Table 19 includes the list of materials by field project and their sources. A representative sample was obtained following AASHTO T248 *Method of Test for Reducing Samples of Aggregate to Testing Size* and ASTM D3665-12 *Standard Practice for Random Sampling of Construction Materials* from each test site. A sample splitter was used to take a 25 lb (11 kg) specimen for compacting in the Proctor molds according to AASHTO T-180 Method D.

Sieve analyses of the GAB and fill material were conducted per AASHTO T-27. To investigate the effect of repeated compaction under the mechanical hammer in the mold, the gradations of the specimens were also determined after compaction, drying, and pulverization in the lab. These results, all from the UMD laboratory, are labeled as "after Proctor".

Figure 46 to Figure 57 presents the gradation curves for:

(1) the JMFs as reported by MDOT SHA labeled as "MDSHA JMF",

(2) the tolerance limits added as "upper bound" and "lower bound",

(3) samples taken from loose aggregate before compaction in the field labeled as "UMD Lab",

(4) gradation after reusing the 25 lb specimens for compacting Proctor molds at all different MCs labeled as "after Proctor".

The field sample gradations mostly fall within the tolerance limit of the JMFs, except for the gradation for the MD482 fill material that is significantly different than the JMF. The after-Proctor gradation curve for I-695 GAB and Texas GAB fall outside the upper tolerance limit.

**Table 18. GAB properties from JMF as reported by MDOT SHA**

| | | **Compaction method:** | T-180 D | T-180 D | T-180 D | T-180 D | T-180 D | T-180 D |
|---|---|---|---|---|---|---|---|---|
| | | **GAB Source:** | Martin Marietta Materials | Martin Marietta Materials | Aggregate Industries | Aggregate Industries | Savage Stone | Vulcan Materials Company |
| | | **Quarry:** | Pinesburg, MD | Texas, MD | Rockville, MD | Bladensburg, MD | Laurel, MD | Fredrick, MD |
| **[mm]** | **sieve** | **Tolerance** | **%passing** | **%passing** | **%passing** | **%passing** | **%passing** | **%passing** |
| 50.8 | 2" | -2% | 100 | 100 | 100 | 100 | 100 | 100 |
| 38.1 | 1 1/2" | +/-5% | 95 | 98 | 100 | 100 | 100 | 100 |
| 19 | 3/4" | +/-8% | 88 | 81 | 80 | 87 | 83 | 82 |
| 9.5 | 3/8" | +/-8% | 67 | 58 | 55 | 69 | 59 | 68 |
| 4.76 | #4 | +/-8% | 45 | 43 | 44 | 54 | 45 | 47 |
| 0.595 | #30 | +/-5% | 12 | 25 | 17 | 14 | 20 | 15 |
| 0.074 | #200 | +/-2% | 4 | 4 | 6 | 5 | 6 | 6 |
| | | **MDD [pcf]** | 142.7 | 149.2 | 147.4 | 149.8 | 154.2 | 144.2 |
| | | **OMC [%]** | 4.4 | 4.6 | 4.9 | 4.3 | 4.4 | 4.5 |

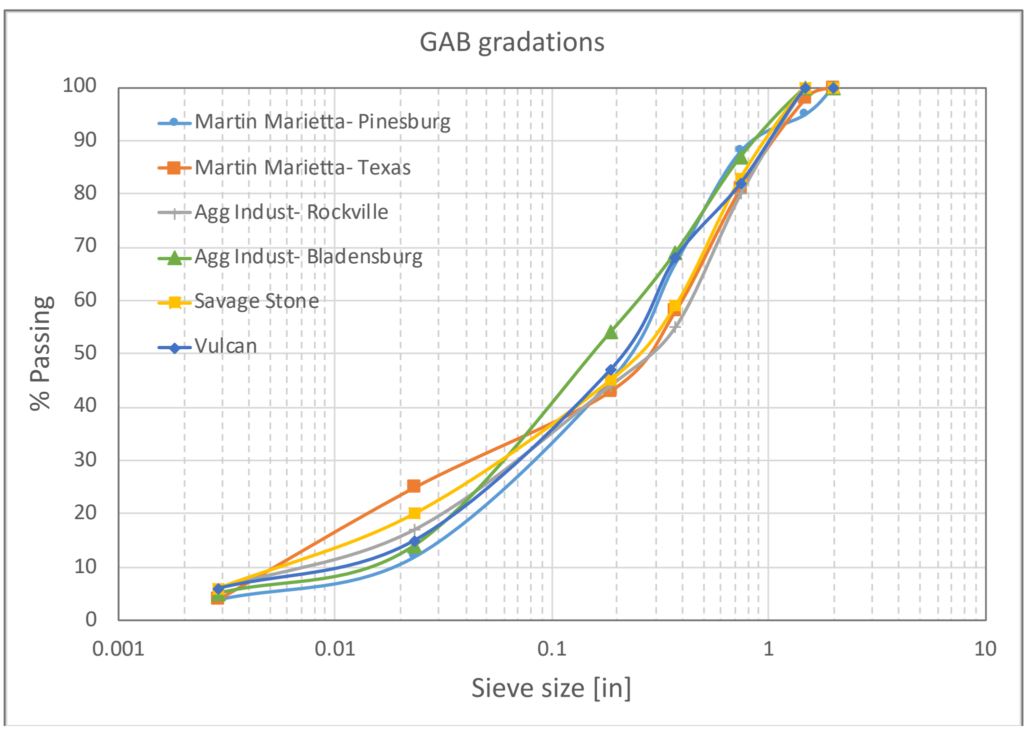



**Figure 45. GAB gradation curves (from JMF as provided by MDOT SHA).**

**Table 19. List of soil sieve analysis performed for gradation determination**

| # | Date | Material label | Aggregate Source |
|---|---|---|---|
| 1 | Fall 17 | I-81 GAB | Martin Marietta Materials, Pinesburg |
| 2 | Fall 17 | MD175 GAB | Savage Stone, Laurel |
| 3 | Fall 17 | MD175 SG section 1 | Select borrow sand A-2-4 subgrade from Fort Meade stockpile A |
| 4 | Fall 17 | MD175 SG section 2 | A-1-b subgrade from East campus of FGGM |
| 5 | Fall 17 | MD5 ramp GAB | Aggregate Industries, Bladensburg |
| 6 | Fall 17 | MD5 ramp embankment | Common borrow, source unknown |
| 7 | Fall 17 | MD482 fill | Common borrow, CJ Miller, Finksburg |
| 8 | Sum 18 | I-270 fill | Common borrow, source unknown |
| 9 | Sum 18 | I-270 fill after Proctor | Common borrow, source unknown |
| 10 | Sum 18 | MD32 R1 GAB | Vulcan Materials Company, Fredrick |
| 11 | Sum 18 | MD32 R2 GAB | Vulcan Materials Company, Fredrick |
| 12 | Sum 18 | MD32 R2 GAB after Proctor | Vulcan Materials Company, Fredrick |
| 13 | Sum 18 | Rockville GAB | Aggregate Industries, Rockville |
| 14 | Sum 18 | Rockville GAB after Proctor | Aggregate Industries, Rockville |
| 15 | Sum 18 | Martin Texas GAB | Martin Marietta Materials, Texas |
| 16 | Sum 18 | Martin Texas GAB after Proctor | Martin Marietta Materials, Texas |
| 17 | Sum 18 | Savage Stone GAB | Savage Stone, Laurel |
| 18 | Sum 18 | Savage Stone GAB after Proctor | Savage Stone, Laurel |
| 19 | Sum 18 | I-95 Bridge fill | CR-6 |
| 20 | Sum 18 | I-95 Bridge fill after Proctor | CR-6 |
| 21 | Sum 18 | MD355 new comp | Common borrow shale, source unknown |
| 22 | Sum 18 | MD355 new comp after Proctor | Common borrow shale, source unknown |
| 23 | Fall 18 | I-695 GAB | Martin Marietta Materials, Texas |
| 24 | Fall 18 | I-695 GAB after Proctor | Martin Marietta Materials, Texas |
| 25 | Fall 18 | MD5 Interchange | Aggregate Industries, Bladensburg |
| 26 | Fall 18 | MD5 Interchange after Proctor | Aggregate Industries, Bladensburg |

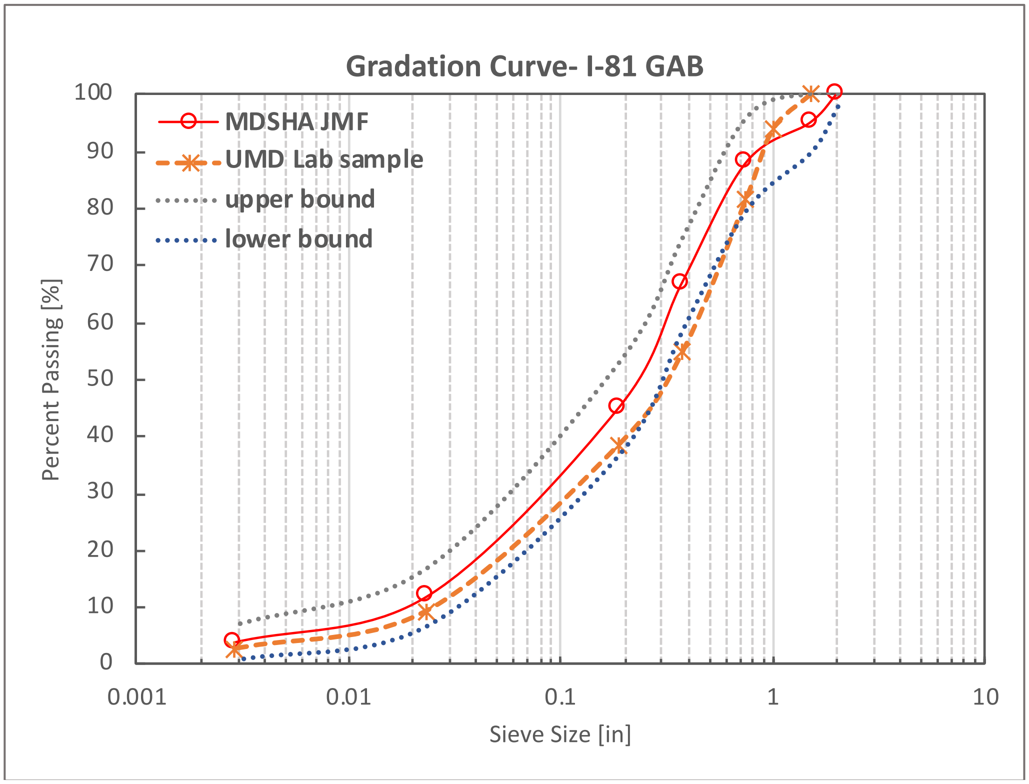



**Figure 46. Gradation curves, I-81 GAB**

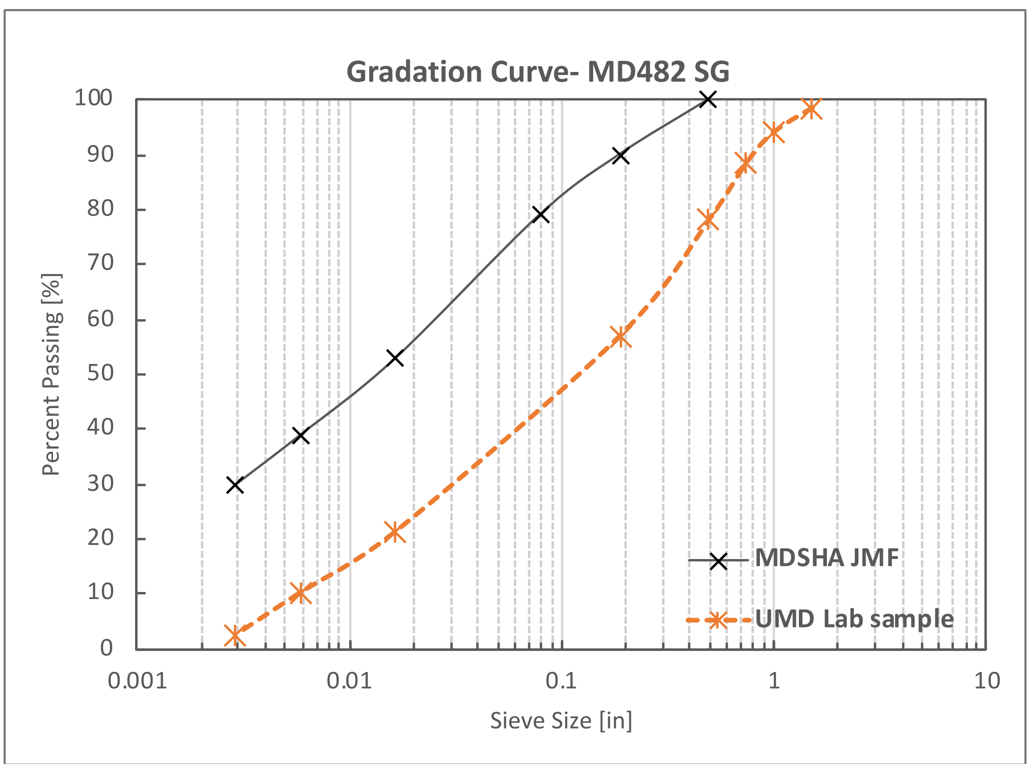



**Figure 47. Gradation curves, MD482 fill material**

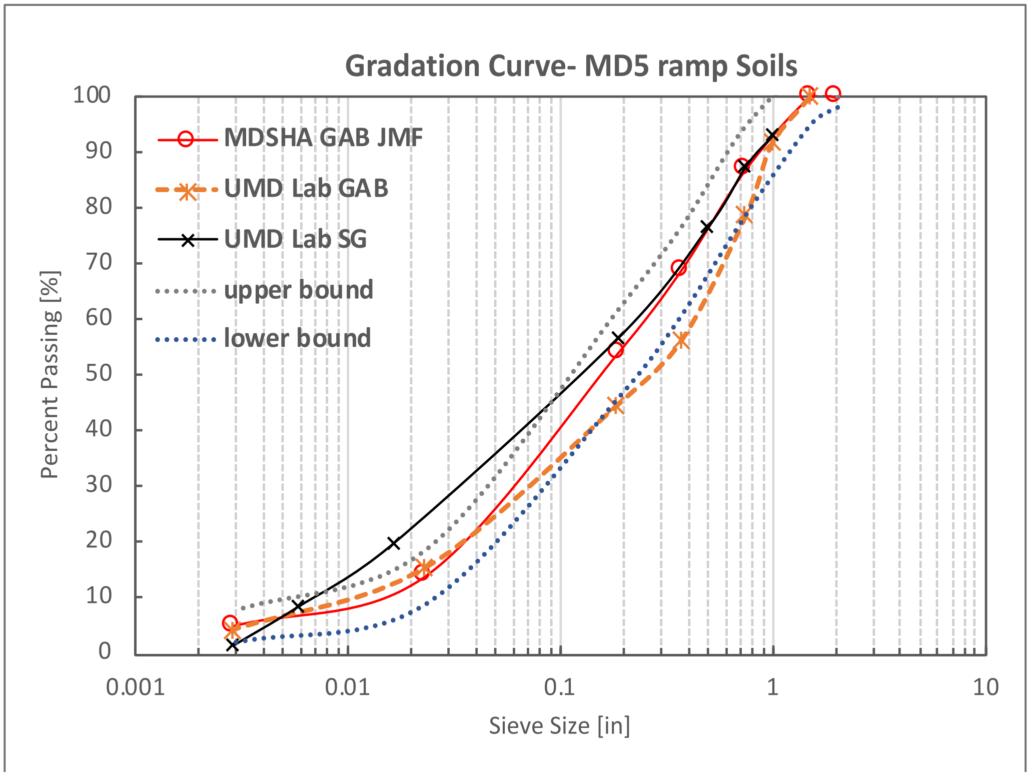



**Figure 48. Gradation curves, MD5 ramp soils**

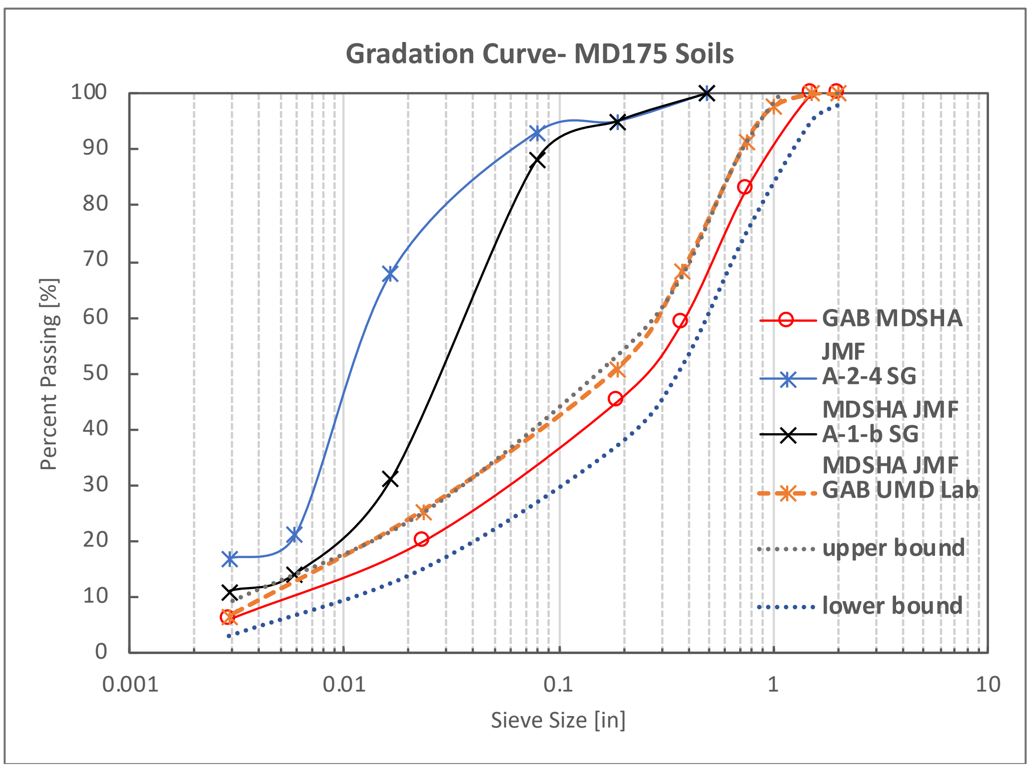



**Figure 49. Gradation curves, MD175 soils**

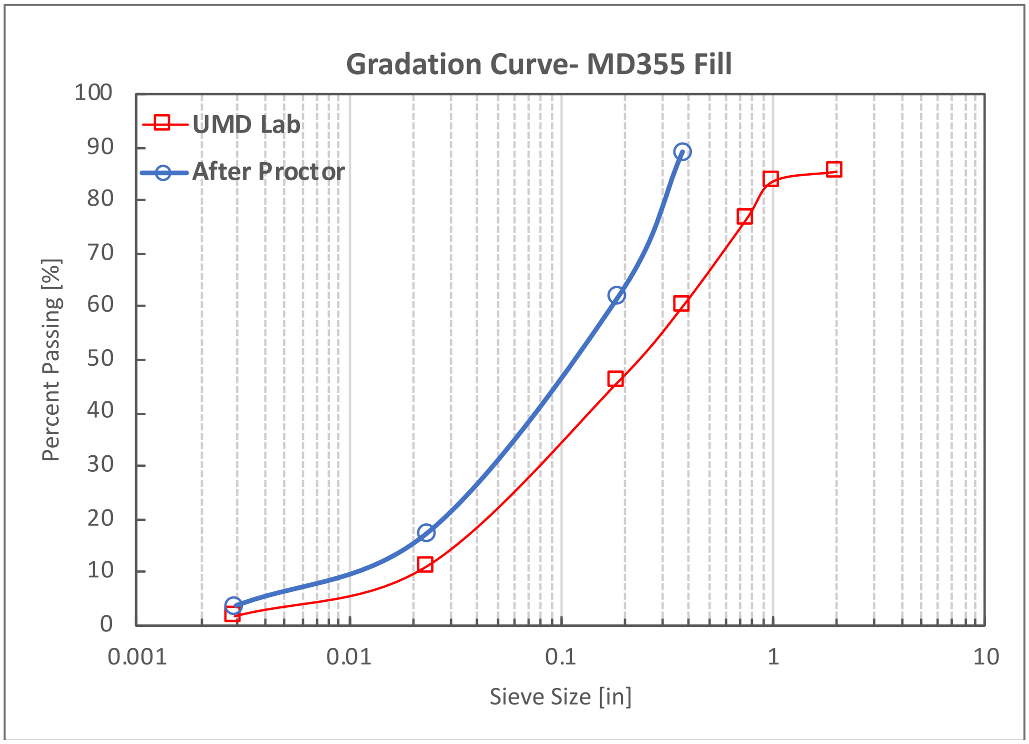


**Figure 50. Gradation curves, MD355 fill material**

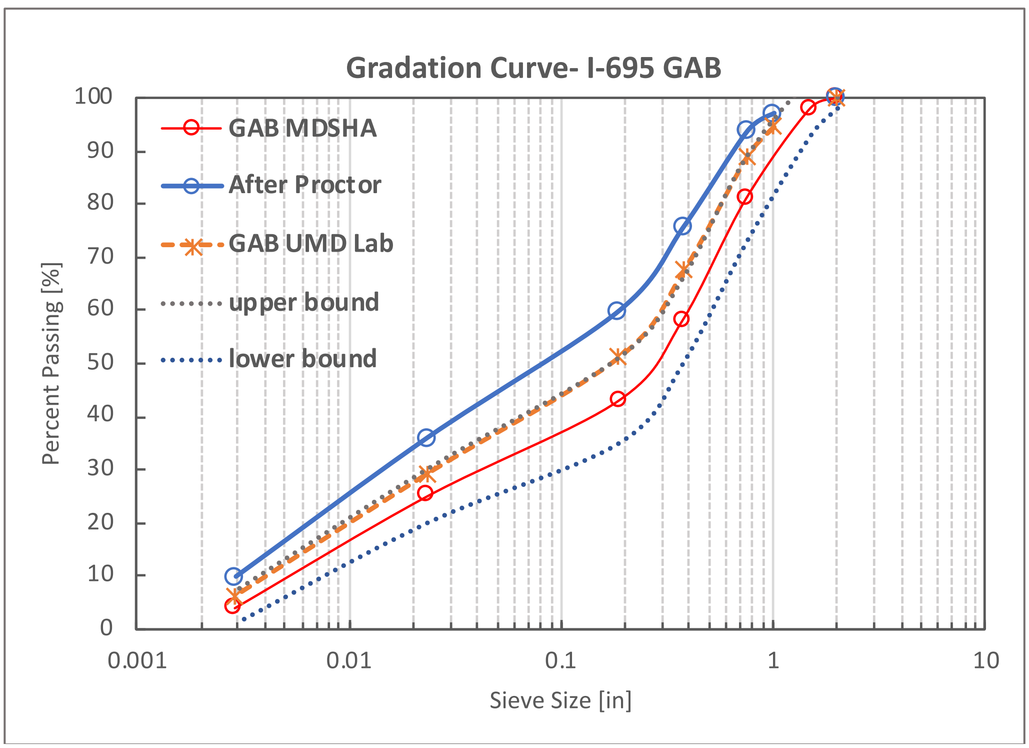


**Figure 51. Gradation curves, I-695 GAB**

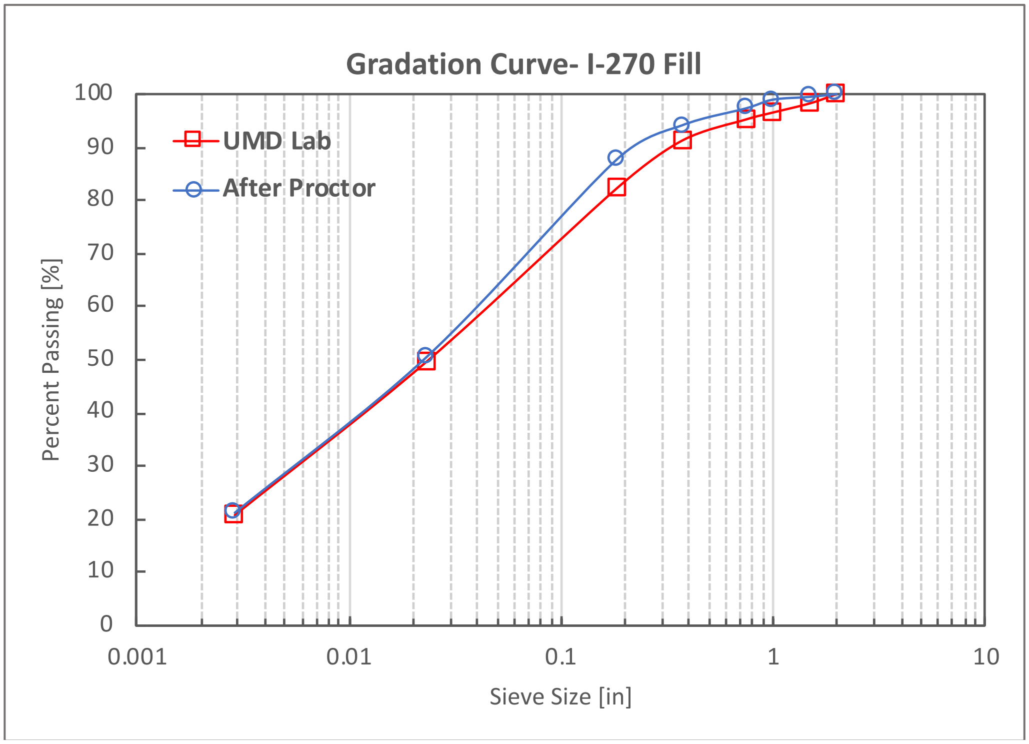



**Figure 52. Gradation curves, I-270 GAB**

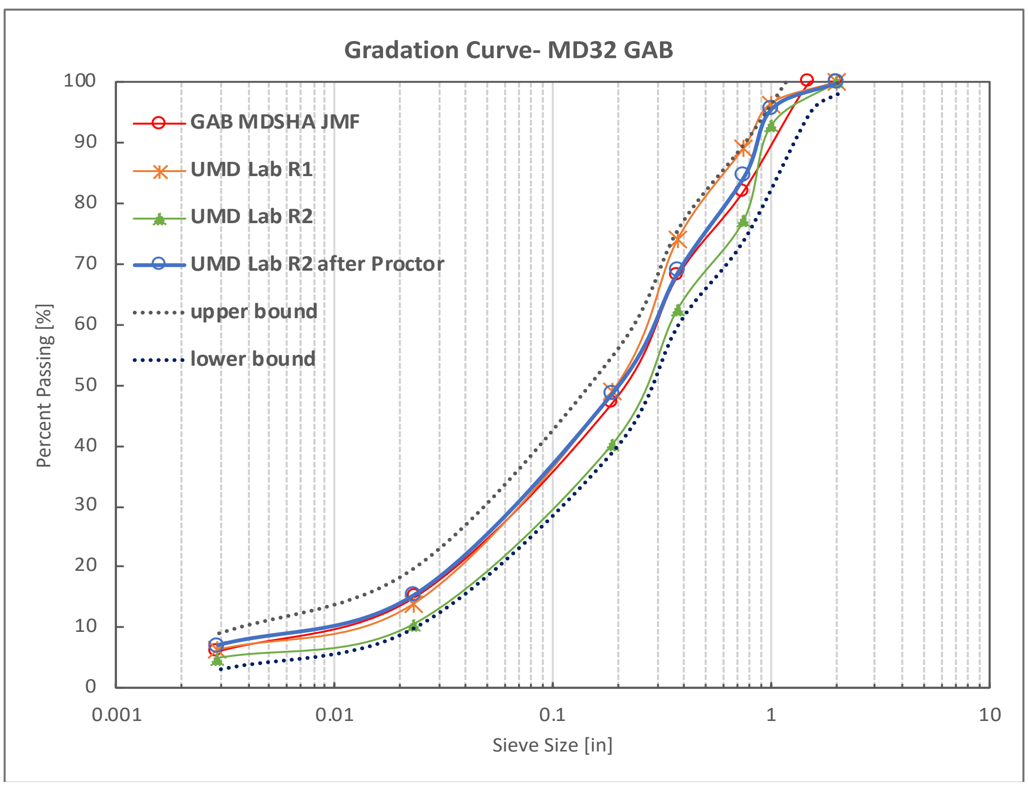



**Figure 53. Gradation curves, MD32 GAB**

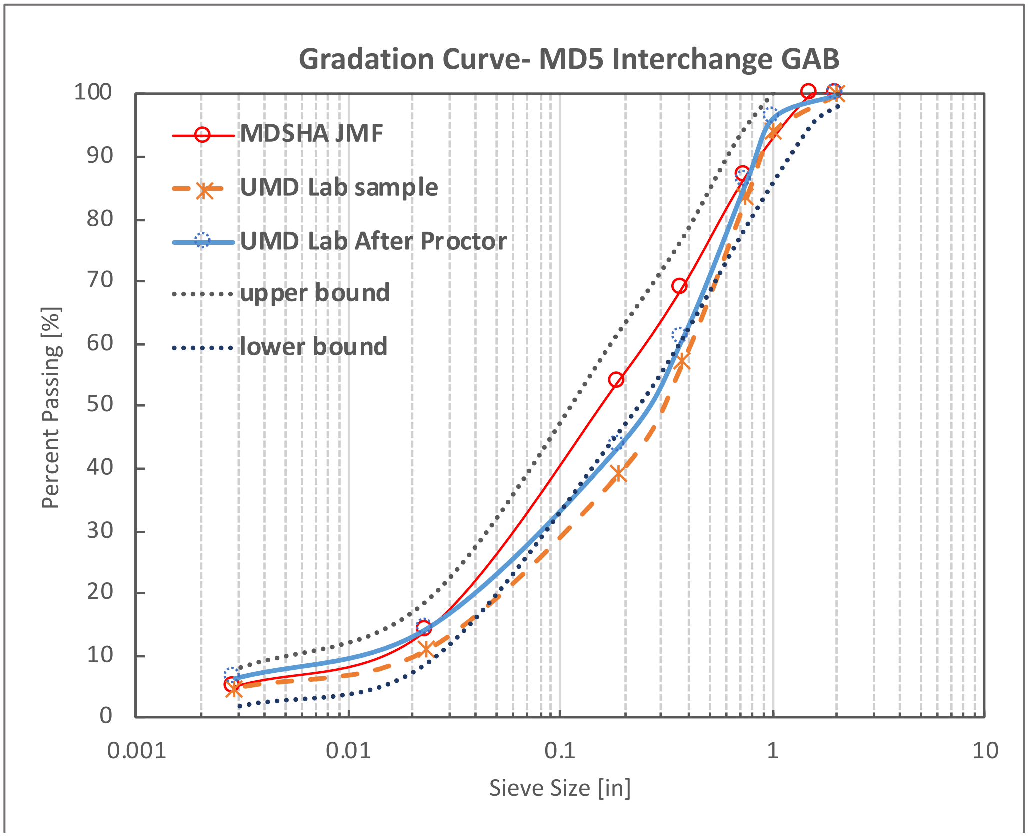



**Figure 54. Gradation curves, MD5 interchange construction GAB**

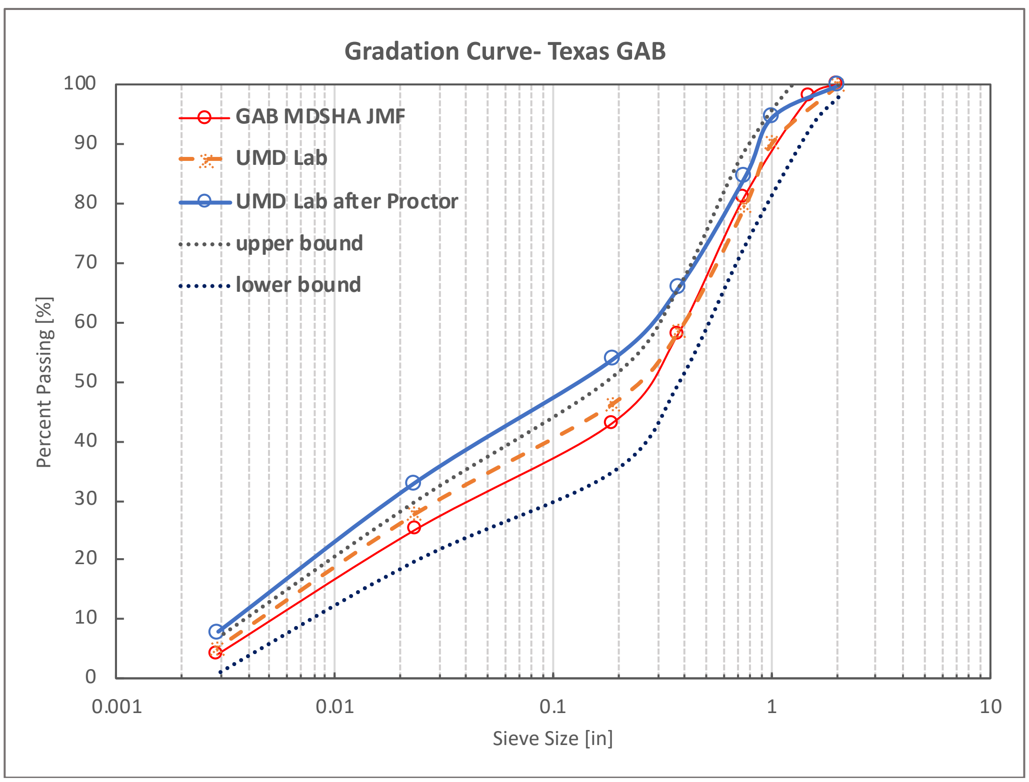



**Figure 55. Gradation curves, Martin Marietta Texas quarry GAB**

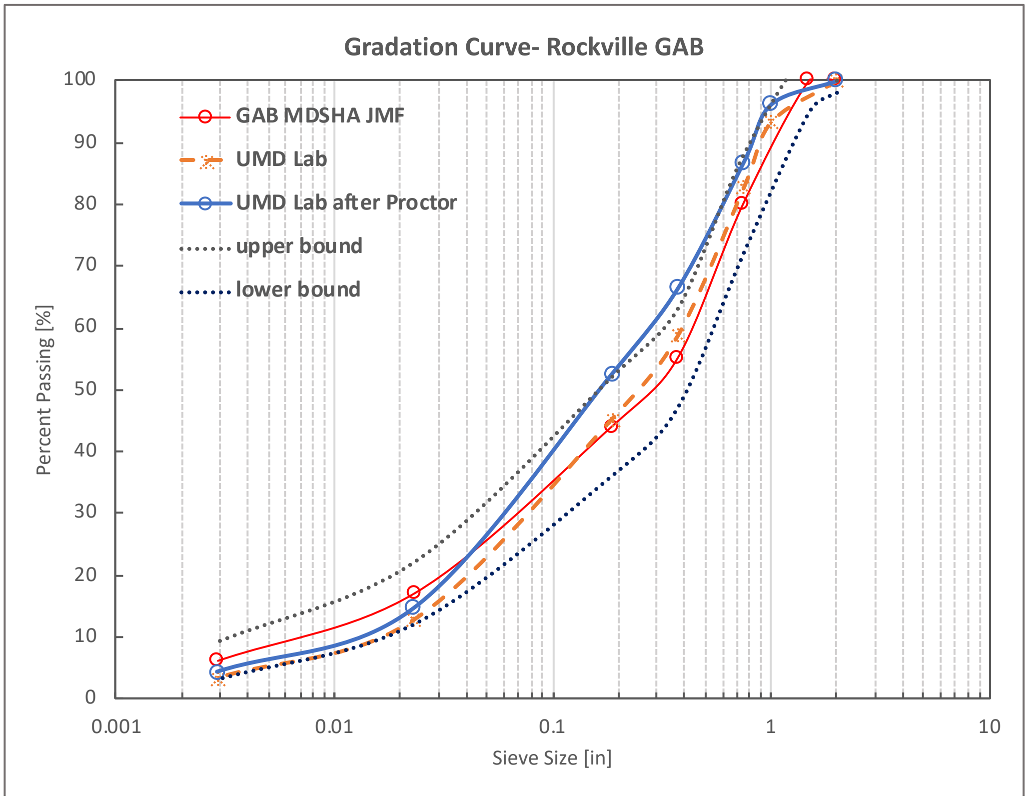



**Figure 56. Gradation curves, Aggregate Industries Rockville quarry GAB**

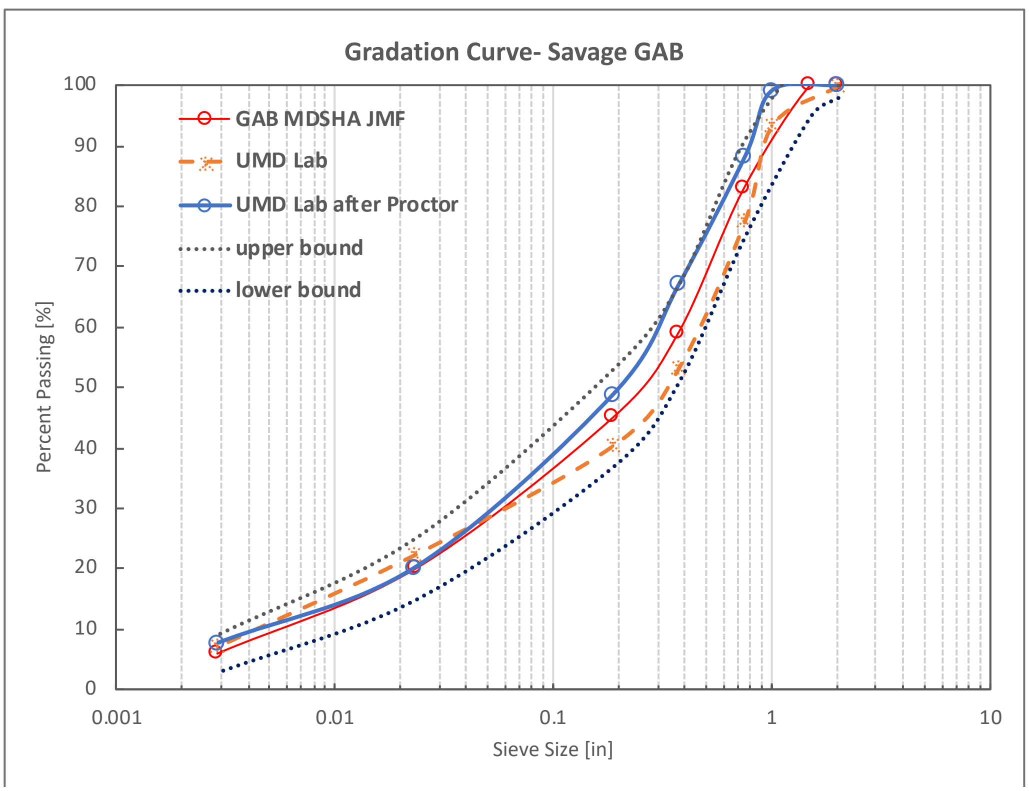



**Figure 57. Gradation curves, Savage Stone GAB**

## 6.2. Field and laboratory testing

LWD testing was performed on the geomaterials locally available for road and embankment construction, and in particular on unbound aggregate bases. PC is used as a reference for the quality of compaction and compared to the field-to-target modulus ratios calculated in this chapter.

### 6.2.1. *LWD testing and data collection in the field*

Suitable construction projects were selected in collaboration with MDOT SHA and field testing was conducted given the schedule and requirements of the projects. Test sites were a minimum of 30 m (100 ft) long. Ten to twenty spots were marked at each site depending on the observed spatial variability and time. Test spots were selected at random locations averaging 3 m (10 ft) apart to cover the length of the strip.

Six LWD drops were performed on each spot within two hours after compaction to minimize the drying effects on the field modulus measurements. The deflections and modulus for each drop were carefully evaluated, and the testing was repeated at an adjacent location if suspected outlier data were observed. LWD testing were also performed on the subgrade prior to the placement and compaction of the base layer to capture the stiffness of underlying layer in order to correct the target modulus for the effect of finite layer thickness.

The Dynatest LWD with a 300 mm loading plate (12 in.), 10 kg (22 lbs) drop weight, two gray and six black buffers combination, and 84 cm (33 in.) drop height was used for field testing. The center plug was used for locking the center deflection sensor to the plate to avoid collecting biased data on graded aggregates and crushed stones.

In order to address MDOT SHA's interest in evaluating the effect of plate size on LWD measurements, a 200 mm (8 in.) plate was used on two test sites as well.

NDG measurements were conducted concurrently with and at the same spots as the LWD testing by a certified technician provided by MDOT SHA. Moisture content samples were also taken from the top 8 cm (3 in.) at each location for oven drying in the lab.

Bulk samples of the geomaterials were collected from each site for laboratory classification, Proctor moisture-density characterization, and LWD on mold testing. Further details on the data collected at each site visit are provided in the Appendix D.

The modulus (E) of the LWD in the field is calculated using the Boussinesq equation (Equation 1). The A factor was assumed to equal to $3/4\pi$ for the Dynatest LWD and Poisson's ratio was assumed equal to 0.35 for all soil types in this chapter. Unless mentioned otherwise, the plate radius equaled 150 mm (6 in.) for all field testing.

### 6.2.2. ***Laboratory testing program***

A sample splitter was used to separate 11 kg (25 lbs) specimen of the bulk samples for compacting the Proctor molds per AASHTO T-180 Method D. Oversize particles were excluded when the total retained on the 50.8 mm (2-in.) sieve was less than 10%. The initial compaction moisture content of the specimen was selected as roughly four percentage points below the material's OMC based on experience or as determined previously by the JMF. Compaction MC was increased until the compaction curve is achieved or significant water drainage was observed from the bottom of the mold. A uniform thickness of material was spread and compacted using the modified energy according to method D. Figure 58 shows the Proctor mold preparation procedure. Three to five moisture contents were evaluated for each soil type (Table 20).

The mold was placed stably on the concrete floor. The 150 mm (6 in.) diameter LWD loading plate was then placed on top of the mold and rotated approximately 45° left and right to seat the plate. The diameter of the LWD plate is almost equal to mold diameter and thus cleared the rim of the mold.

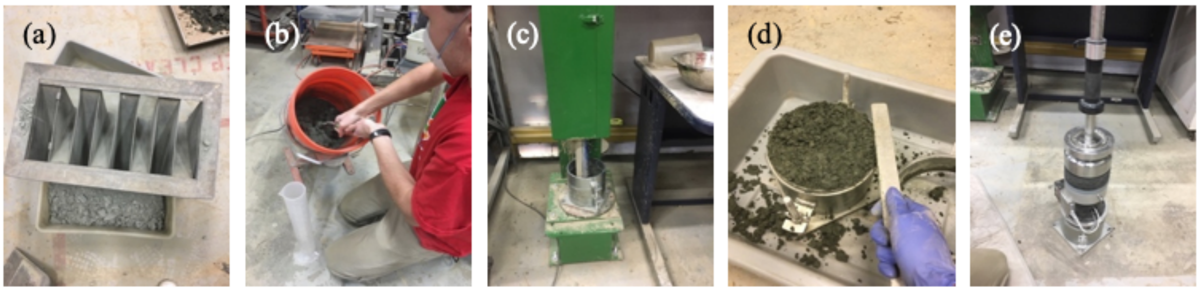



**Figure 58. Proctor mold preparation and LWD on mold testing; (a) separating test specimen using sample splitter, (b) thoroughly mixing the soil with water, (c) compacting the mold using mechanical compactor, (d) leveling the surface for full contact with the LWD plate, (e) resting the mold on the concrete floor and placing LWD on top of the mold to perform drops.**

Holding the LWD rod vertical, six drops at each drop height were conducted. Three seating drops followed by three measurement drops were performed by raising the weight to each reduced drop height (3,4,5,6, and 8 in.), then allowing the weight to fall freely without lateral movements. Drops started from the lowest drop height and then increased the height. Thirty total drops on each mold were performed to evaluate the stress dependency of material and permit interpolation/extrapolation of measured moduli values to the field plate pressure.

It was confirmed during the testing that the force generated by the drop followed a haversine history with pulse durations between 20 and 40 msecs for the Dynatest LWD (Section 5.3, ASTM E 2583). The load pulse duration depends on the soil modulus and can be adjusted by altering the LWD buffer stiffness, plate size, and drop mass weight.

The deflections, applied loads, and other data were automatically recorded from each drop in the Dynatest PDA (data receiver) and then exported to Excel sheets using the Dynatest *LWDmod* software for modulus calculations and further processing.

**Table 20. List of LWD on mold tests performed for different soil types at different MC.**

| # | Material label | Aggregate Source | Tested Molds | MC1 | MC2 | MC3 | MC4 | MC5 |
|---|---|---|---|---|---|---|---|---|
| 1 | I-81 GAB | Martin Marietta Materials, Pinesburg | 4 | 2 | 3 | 4.5 | 6 | _ |
| 2 | I-81 GAB excluded oversize 3/4" | Martin Marietta Materials, Pinesburg | 4 | 2 | 3 | 5 | 7 | _ |
| 3 | MD175 GAB | Savage Stone, Laurel | 5 | 3 | 4 | 6 | 7 | 8 |
| 4 | MD175 GAB excluded oversize 3/4" | Savage Stone, Laurel | 3 | 4 | 6 | 8 | _ | _ |
| 5 | MD5 ramp GAB | Aggregate Industries, Bladensburg | 5 | 2.5 | 3.5 | 4.5 | 6 | 8 |
| 6 | MD5 ramp GAB excluded oversize 3/4" | Aggregate Industries, Bladensburg | 3 | 2.5 | 4.5 | 6 | _ | _ |
| 7 | MD482 fill | Common borrow, CJ Miller, Finksburg | 4 | 5 | 8 | 9 | 12 | _ |
| 8 | MD482 fill excluded oversize 3/4" | Common borrow, CJ Miller, Finksburg | 3 | 7 | 9 | 11 | _ | _ |
| 9 | I-270 fill | Common borrow, source unknown | 5 | 7 | 9 | 11 | 13 | 15 |
| 11 | MD32 R2 | Vulcan Materials Company, Fredrick | 3 | 3 | 4 | 5 | _ | _ |
| 12 | MD32 R2 excluded oversize 3/4" | Vulcan Materials Company, Fredrick | 3 | 3 | 4 | 5 | _ | _ |
| 13 | Rockville GAB | Aggregate Industries, Rockville | 4 | 4 | 5 | 6 | 7 | _ |
| 14 | Rockville GAB excluded oversize 3/4" | Aggregate Industries, Rockville | 4 | 4 | 5 | 6 | 7 | _ |
| 15 | Martin Texas GAB | Martin Marietta Materials, Texas | 3 | 3 | 4 | 5 | _ | _ |
| 16 | Martin Texas GAB excluded oversize 3/4" | Martin Marietta Materials, Texas | 4 | 3 | 4 | 5 | 6 | _ |
| 17 | Savage Stone GAB | Savage Stone, Laurel | 4 | 3 | 4 | 5 | 6 | _ |
| 18 | Savage Stone GAB excluded oversize 3/4" | Savage Stone, Laurel | 4 | 3 | 4 | 5 | 6 | _ |
| 19 | I-95 Bridge CR-6 fill | Source unknown | 3 | 3 | 5 | 6 | _ | _ |
| 22 | MD355 new comp exclude oversize 3/4" | Common borrow shale, source unknown | 4 | 6.5 | 7.5 | 8.5 | 9.5 | _ |
| 23 | I-695 GAB | Martin Marietta Materials, Texas | 3 | 3 | 4 | 5 | _ | _ |
| 24 | MD5 Interchange | Aggregate Industries, Bladensburg | 4 | 3 | 4 | 5 | _ | _ |
| 25 | Rockville GAB (Redo) | Aggregate Industries, Rockville | 3 | 4 | 5 | 6 | _ | _ |
| | | **Total** | **82** | | | | | |

It should be noted that when the soil material is fragile and the grain size distribution may be altered significantly by repeated compaction. Ideally, a separate and new soil sample should be used for each test, although sufficient material may not always be available to make this possible, as was the case here. At the end of each test, the material from the mold was removed, and representative samples were taken immediately to determine the MC in the oven per AASHTO T-265.

The rest of the material was returned to the mixing bowl and the MC was increased for compaction of the next mold if needed. This conforms to the common practice at the MDOT SHA soils laboratory.each compaction test (AASHTO T-180, Section 5.4.1). To investigate the effect of reusing material, selected specimens were oven dried and pulverized for sieve analysis after compaction. This is described further in Section 6.3.5 in this chapter.

To assess the repeatability of the data, LWD on mold tests were repeated four times for two GAB materials (Table 21). One material came directly from the source quarry and the other from a field project using the same source aggregate.

The TPF-5(285) mold preparation procedure recommends including all particles passing the 2 in. (50.8mm) sieve in order to maintain the original gradation during modulus measurement. However, the AASHTO T-180 requires scalping off material retained above the ¾ in. (19.05 mm) sieve if 30% or less of the total sample weight. The MDD and OMC are then corrected per AASHTO T-224. To investigate the effect of oversize particles (retaining on ¾" sieve) on target modulus measured in the LWD on mold test, testing was performed for the full and scalped gradations for a few GABs in this study (Table 22).

**Table 21. GABs tested to check the repeatability of the LWD on mold results.**

| # | Sample (1) | Sample (2) |
|---|---|---|
| 1 | I-695 GAB | Martin Marietta Materials, Texas |
| 2 | Aggregate Industries, Rockville | Aggregate Industries, Rockville |

**Table 22. Soils used to evaluate the effect of reusing samples in the Proctor test.**

| # | Material label | Aggregate Source |
|---|---|---|
| 1 | Martin Texas GAB, Quarry Sample | Martin Marietta Materials, Texas |
| 2 | I-695 GAB | Martin Marietta Materials, Texas |
| 3 | Rockville GAB, Quarry Sample | Aggregate Industries, Rockville |
| 4 | MD5 Interchange | Aggregate Industries, Bladensburg |
| 5 | MD32 R2 GAB | Vulcan Materials Company, Fredrick |
| 6 | Savage Stone GAB, Quarry Sample | Savage Stone, Laurel |
| 7 | MD355 new comp | Common borrow shale, source unknown |
| 8 | I-270 fill | Common borrow, source unknown |
| 9 | I-95 Bridge fill | CR-6 |

### 6.2.3. *Matching LWD field pressure to the LWD on mold pressure*

Different drop heights are performed in the LWD on mold laboratory tests to investigate the stress dependency of LWD modulus (E) and for interpolation/extrapolation to find the target modulus at the field testing pressure. In order to avoid performing drops from multiple drop heights, a single pressure and corresponding drop height can be selected to match the field and lab pressures.

Table 23 presents the different drop heights and the corresponding applied load, calculated pressure (load divided by the plate area), and normalized pressure P/Pa (pressure divided by atmospheric pressure) for the Dynatest LWD with the 22 lb. drop weight and 6 in. (150 mm) diameter plate size on the mold. The relationship between applied load and drop height on the mold is given in Figure 59.

Note that the values in Table 23 are subjected to change if there are modifications to the configuration of the Dynatest LWD or if another LWD is used. However, a similar approach can be used to find the appropriate drop height for a given field pressure for other configurations or LWD types.

The Dynatest LWD with a 10 kg drop weight, 300 mm plate size, and 83 cm drop height was used in the field. It was observed that the applied load in the field ranged from 6.45 kN (1450 lbs.) to 6.88 kN (1547 lbs.) depending on the soil type. This corresponds to a P/Pa range of about 0.90 to 0.98. An average P/Pa of 0.94 can be used for calculation the target modulus from the LWD on mold tests.

The single laboratory drop height to match the P/Pa of 0.94 corresponds to an applied force of 1.68 kN (378.4 lbs.) for the 150 mm plate diameter on the mold. From Figure 59, this gives a single laboratory drop height value of 10.56 cm (4.16 in).

Table 24 summarizes the calculation for an applied load of 6.73 kN (1513.5 lbs) in the field.

**Table 23. LWD on mold drop heights and corresponding applied load, pressure, and normalized pressure.**

| Drop height | Drop height | Avg load | Avg load | Pressure (P) | Pressure (P) | P/Pa |
|---|---|---|---|---|---|---|
| [cm] | [inch] | [kN] | [lbs] | [kPa] | [psf] | [-] |
| 7.62 | 3 | 1.30 | 292.25 | 73.56 | 1536.77 | 0.73 |
| 10.16 | 4 | 1.60 | 359.70 | 90.54 | 1891.41 | 0.89 |
| 12.7 | 5 | 2.00 | 449.62 | 113.18 | 2364.26 | 1.12 |
| 15.24 | 6 | 2.30 | 517.06 | 130.15 | 2718.90 | 1.28 |
| 20.32 | 8 | 2.73 | 614.48 | 154.68 | 3231.16 | 1.53 |

*Pa=2.116 ksf (101.325 kPa)

**Table 24. Matching LWD pressure in the field and on the mold**

| | Plate size | P/Pa | P | P | Force | Force | Drop Height |
|---|---|---|---|---|---|---|---|
| | [inch] | - | [kPa] | [psf] | [kN] | [lbs] | [inch] |
| Field LWD | 12 | 0.94 | 95.25 | 1989.7 | 6.73 | 1513.5 | 33.00 |
| Lab LWD | 6 | 0.94 | 95.25 | 1989.7 | 1.68 | 378.4 | 4.16 |

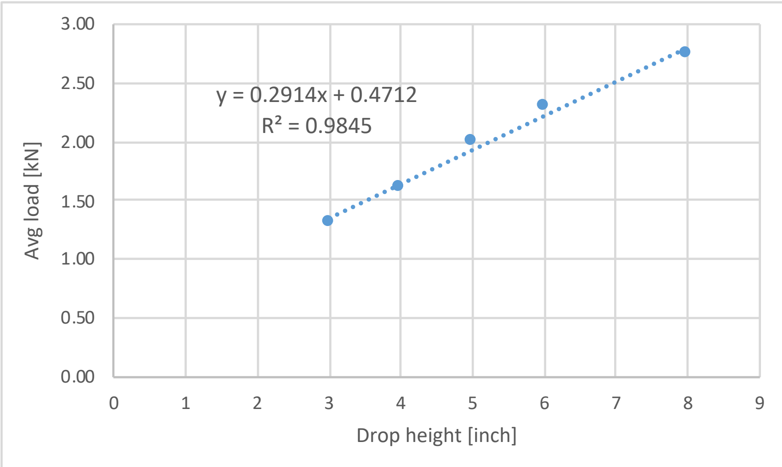



**Figure 59. Dynatest LWD average applied load at different drop heights on the mold.**

## 6.3. Results

In this section, the $E_{field}/E_{target}$ was calculated for Maryland unbound materials. PC was also measured for each site/material. Previous studies and testing exhibit that density and modulus are not perfectly correlated (Mooney et al. 2003, Mooney et al. 2010).

Well-compacted test sections should pass both the PC and $E_{field}/E_{target}$ criteria, while the expectation is that sites with inadequate compaction will to meet both PC and $E_{field}/E_{target}$ criteria.

### 6.3.1. *LWD measurements in the field*

Table 25 summarizes the results of the LWD testing for the test sites in the state of Maryland. The average LWD modulus (averaged for the 10-20 testing spots) ranged between 21 to 165 MPa to with a maximum coefficient of variation (COV) of about 52%.

**Table 25. Summary of LWD and NDG measurements for the tested soils (SD = standard deviation, COV = coefficient of variation).**

| | LWD field modulus | | | LWD field deflection | | | LWD load | | LWD Pressure | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Project** | **Avg [MPa]** | **SD** | **COV [%]** | **Avg [Micron]** | **SD** | **COV [%]** | **Avg [kN]** | **SD** | **Avg [kPa]** | **SD** |
| I-81 GAB | 62.56 | 15.13 | 24.18 | 573.98 | 186.53 | 32.50 | 6.71 | 0.06 | 94.90 | 0.80 |
| MD5 ramp SG | 125.88 | 56.39 | 44.80 | 308.13 | 114.52 | 37.17 | 6.72 | 0.05 | 95.12 | 0.74 |
| MD5 ramp GAB R1 | 159.50 | 30.33 | 19.02 | 216.00 | 38.66 | 17.90 | 6.73 | 0.05 | 95.20 | 0.69 |
| MD5 ramp GAB R2 | 165.85 | 37.34 | 22.51 | 207.83 | 38.46 | 18.51 | 6.69 | 0.05 | 94.64 | 0.70 |
| MD482 fill | 21.96 | 9.96 | 45.36 | 1690.97 | 644.27 | 38.10 | 6.45 | 0.12 | 91.25 | 1.68 |
| MD175 A-2-4 SG | 142.89 | 73.84 | 51.67 | 286.29 | 107.89 | 37.69 | 6.84 | 0.06 | 96.82 | 0.84 |
| MD175 A-1-b SG | 88.77 | 36.99 | 41.66 | 496.71 | 364.71 | 73.43 | 6.83 | 0.08 | 96.57 | 1.14 |
| MD175 GAB R1 | 112.09 | 55.87 | 49.85 | 381.11 | 185.08 | 48.56 | 6.84 | 0.06 | 96.76 | 0.88 |
| MD175 GAB 2 | 128.05 | 59.49 | 46.46 | 325.07 | 165.44 | 50.89 | 6.70 | 0.06 | 94.74 | 0.90 |
| MD355 fill | 49.78 | 9.65 | 19.39 | 679.42 | 126.87 | 18.67 | 6.60 | 0.07 | 93.37 | 0.98 |
| I-695 GAB | 77.35 | 13.84 | 17.89 | 442.83 | 94.90 | 21.43 | 6.67 | 0.04 | 94.31 | 0.59 |
| I-270 fill | 50.70 | 10.21 | 20.14 | 672.20 | 140.86 | 20.96 | 6.61 | 0.06 | 93.51 | 0.92 |
| MD32 GAB R1 | 51.54 | 11.73 | 22.76 | 617.30 | 183.98 | 29.80 | 6.61 | 0.06 | 93.56 | 0.81 |
| MD32 GAB R2 | 67.16 | 12.03 | 17.91 | 509.63 | 98.62 | 19.35 | 6.68 | 0.05 | 94.50 | 0.74 |
| MD5 Int. GAB | 48.28 | 10.80 | 22.37 | 711.33 | 178.00 | 25.02 | 6.57 | 0.05 | 92.99 | 0.76 |

### 6.3.2. *LWD measurements on the mold*

LWD drops performed from various drop heights on compacted proctor molds at different GWC. At least three different water contents were used for each material at each set of tests to reach the compaction curve per AASHTO T-180 Method D. A quadratic trend line is fitted for the dry density data with Microsoft Excel to show the best Proctor curve. It should be noted that MDOT SHA uses the Geosystem Software to find the MDD based on lab MC and weight measurements.

Figure 60 to Figure 80 present the results of this test. The Dynatest LWD modulus on mold values are superimposed on the Proctor curve and color coded for the different P/Pa values:

- GWC: gravimetric water content, equal to MC

- E_DM: Dynatest LWD modulus on Proctor mold
- Legend shows variable P/Pa (0.73, 0.89, up to 1.45) corresponding to different drop heights (1, 2, up to 8 in.)

Figure 60 to Figure 80 confirm the moisture dependency, stress dependency, and non-linearity of the modulus with respect to these factors. The LWD modulus on mold decreasing with increasing GWC is the overall trend observed. The modulus drops significantly on the wet side of OMC.

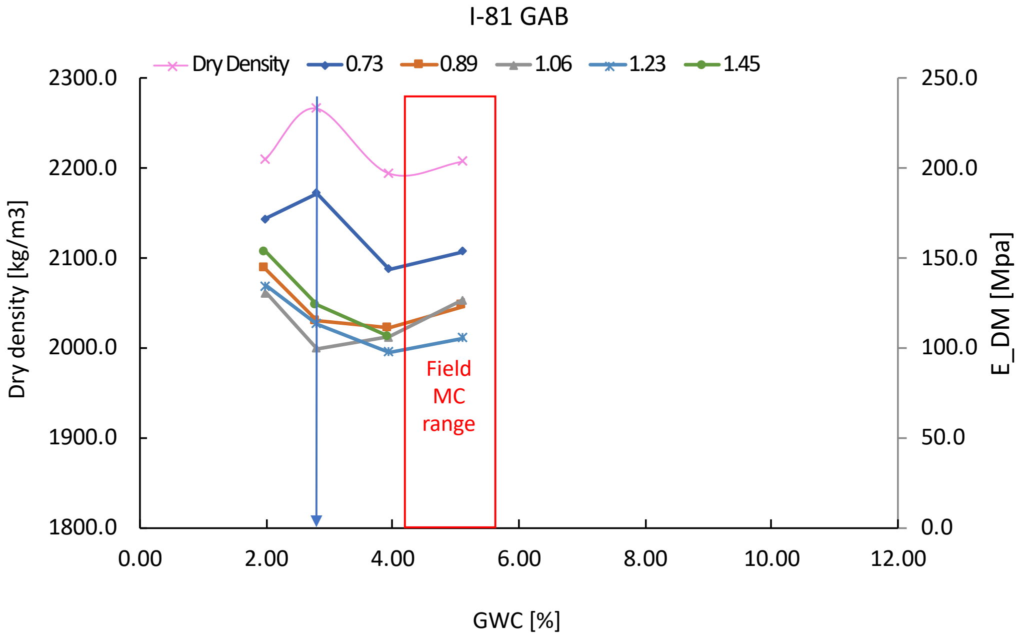



**Figure 60. Dynatest LWD modulus on mold superimposed on dry density versus GWC for I-81 GAB at variable P/Pa.**

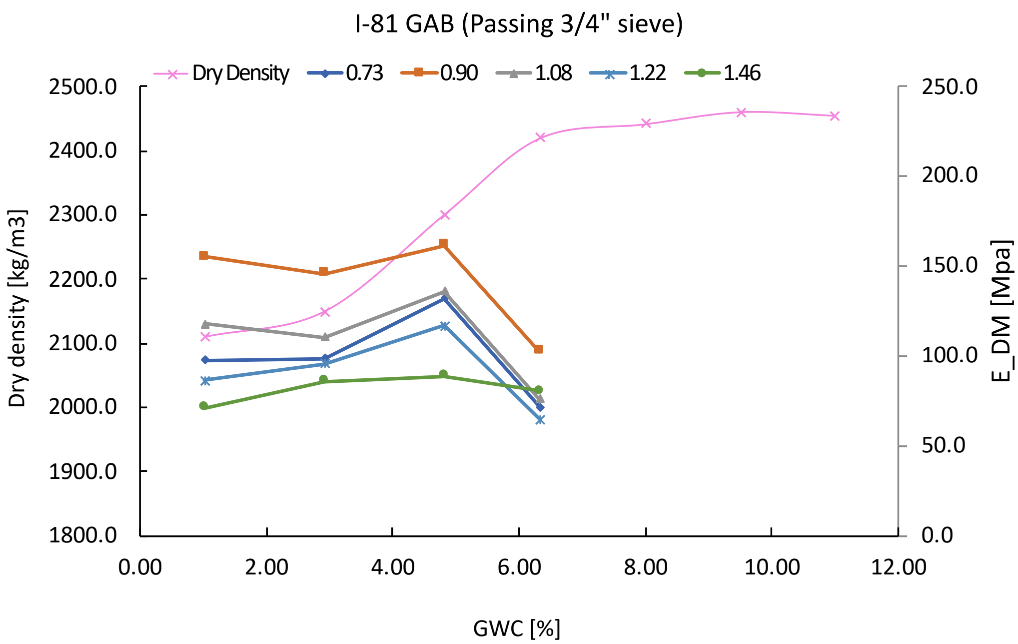



**Figure 61. Dynatest LWD modulus on mold superimposed on dry density versus GWC for I-81 GAB excluded oversized particles at variable P/Pa.**

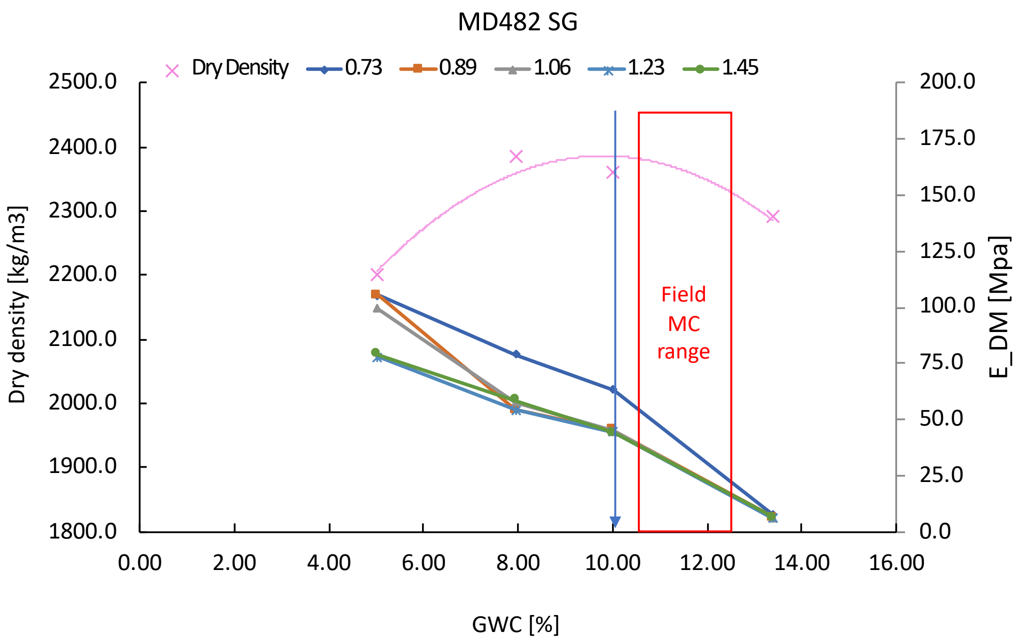



**Figure 62. Dynatest LWD modulus on mold superimposed on dry density versus GWC for MD482 SG at variable P/Pa.**

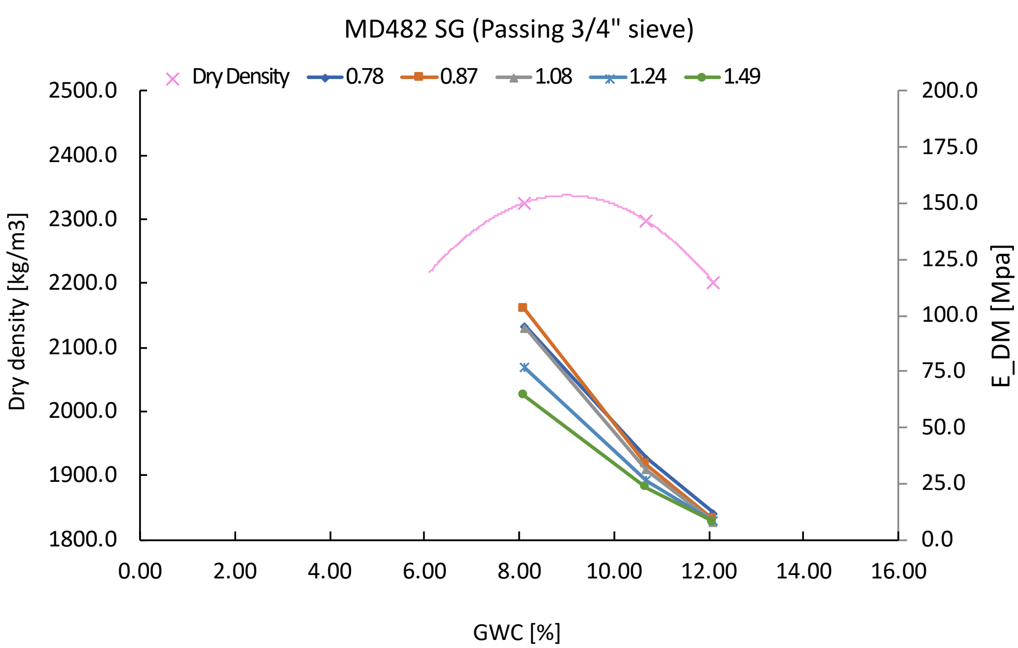



**Figure 63. Dynatest LWD modulus on mold superimposed on dry density versus GWC for MD482 SG excluded oversized particles at variable P/Pa.**

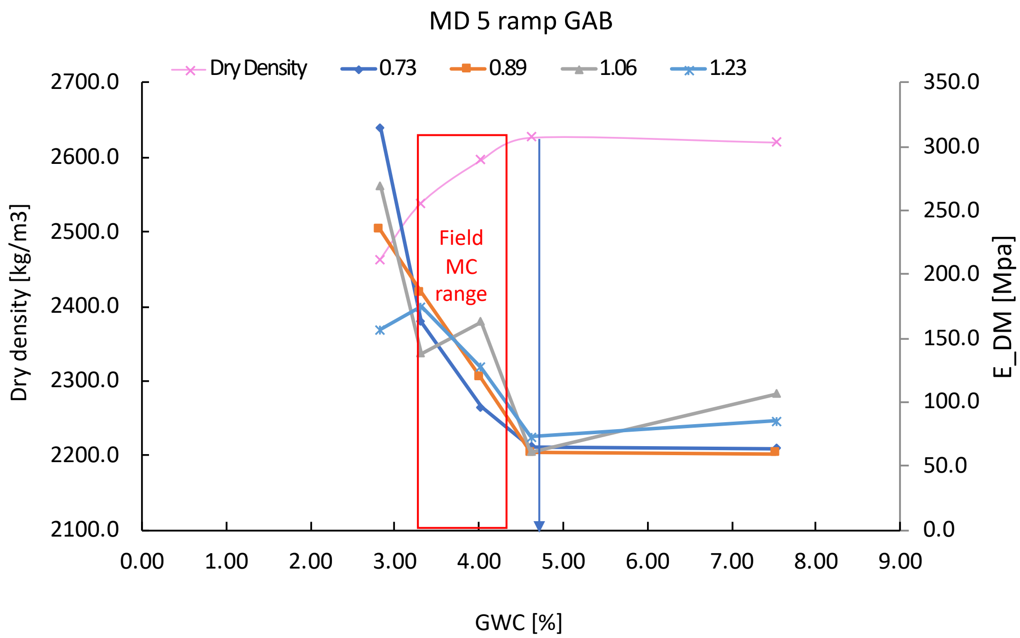



**Figure 64. Dynatest LWD modulus on mold superimposed on dry density versus GWC for MD5 ramp GAB at variable P/Pa.**

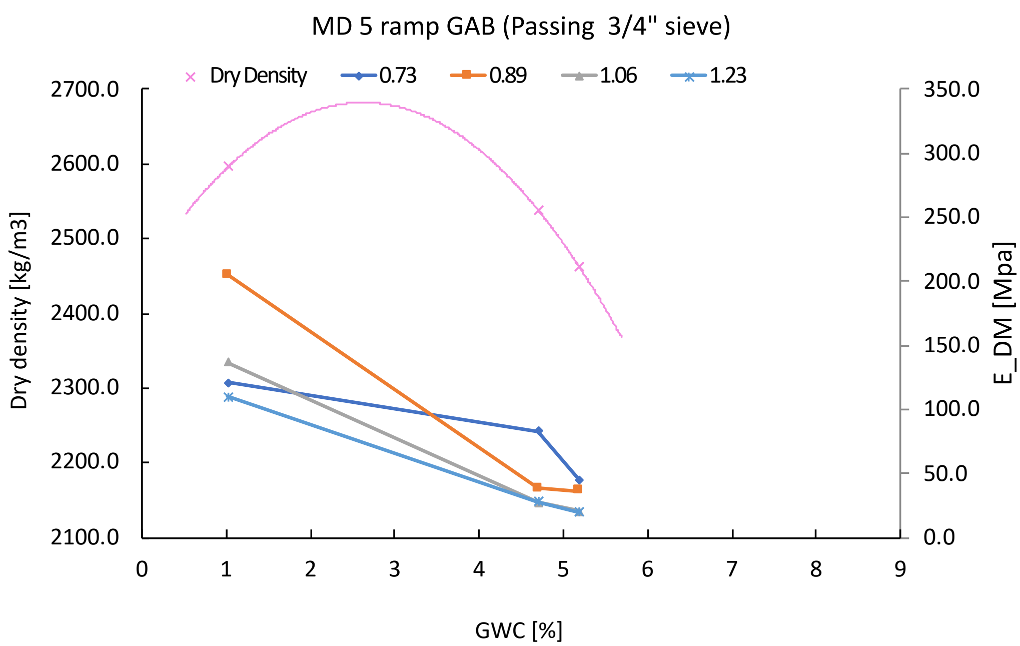



**Figure 65. Dynatest LWD modulus on mold superimposed on dry density versus GWC for MD5 ramp GAB excluded oversized particles at variable P/Pa.**

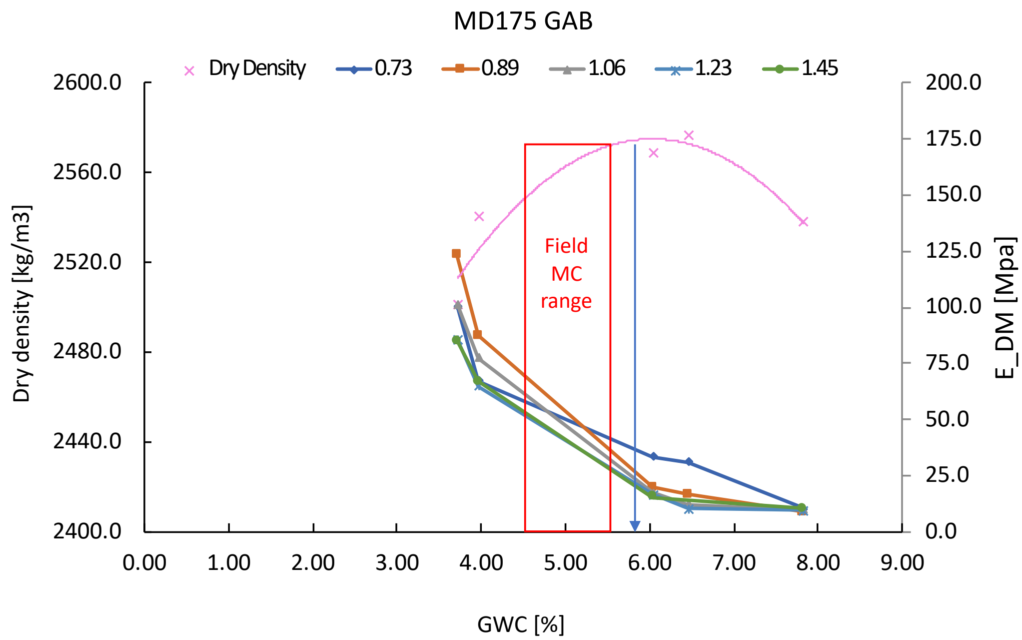



**Figure 66. Dynatest LWD modulus on mold superimposed on dry density versus GWC for MD175 GAB at variable P/Pa**

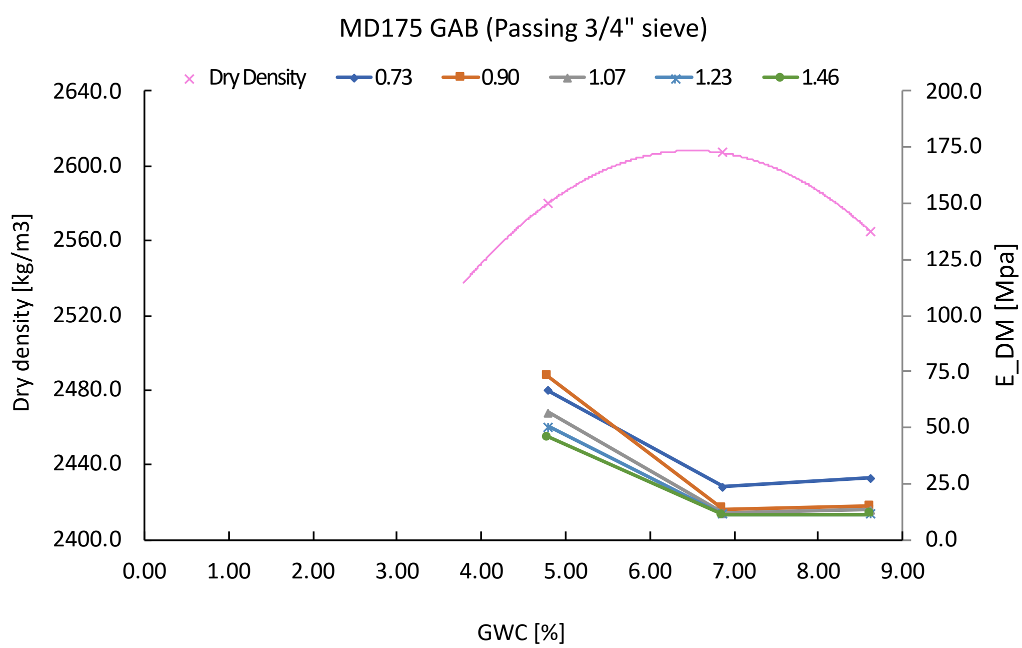



**Figure 67. Dynatest LWD modulus on mold superimposed on dry density versus GWC for MD175 GAB excluded oversized particles at variable P/Pa.**

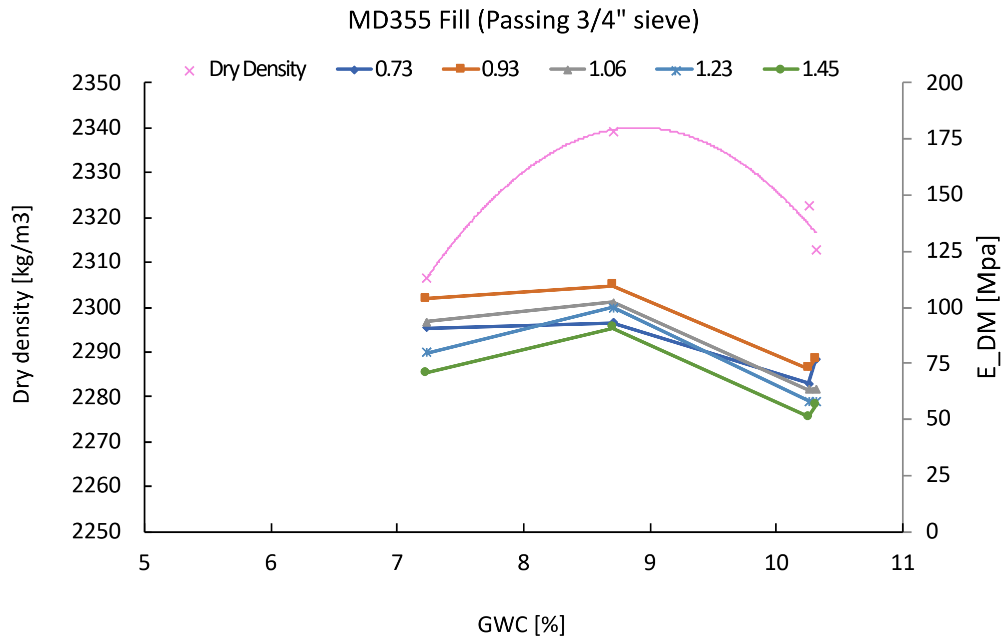



**Figure 68. Dynatest LWD modulus on mold superimposed on dry density versus GWC for MD355 GAB excluded oversized particles at variable P/Pa.**

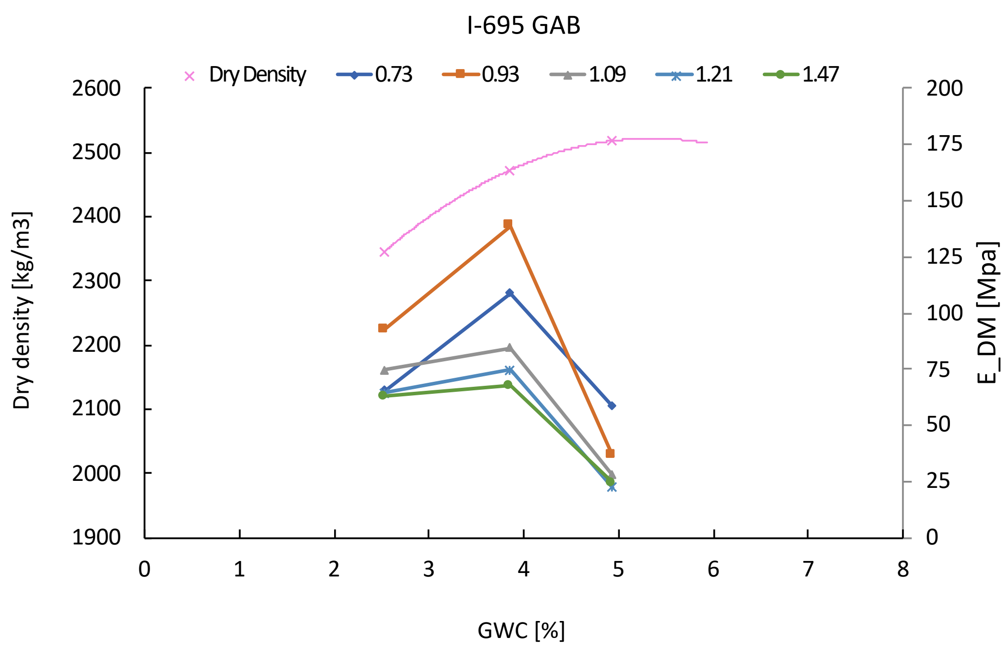



**Figure 69. Dynatest LWD modulus on mold superimposed on dry density versus GWC for I-695 GAB at variable P/Pa.**

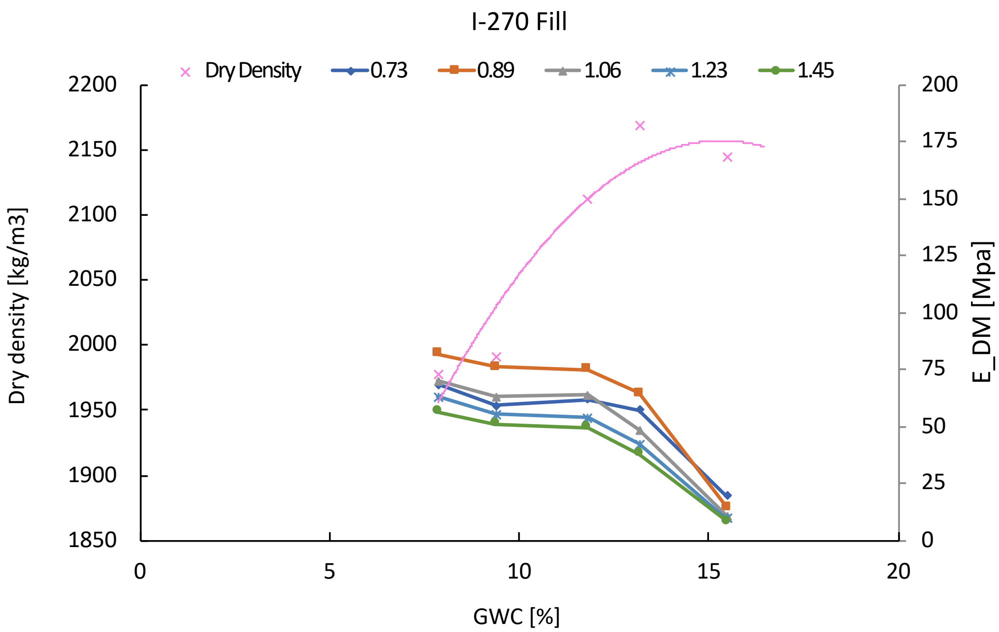



**Figure 70. Dynatest LWD modulus on mold superimposed on dry density versus GWC for I-270 fill material at variable P/Pa.**

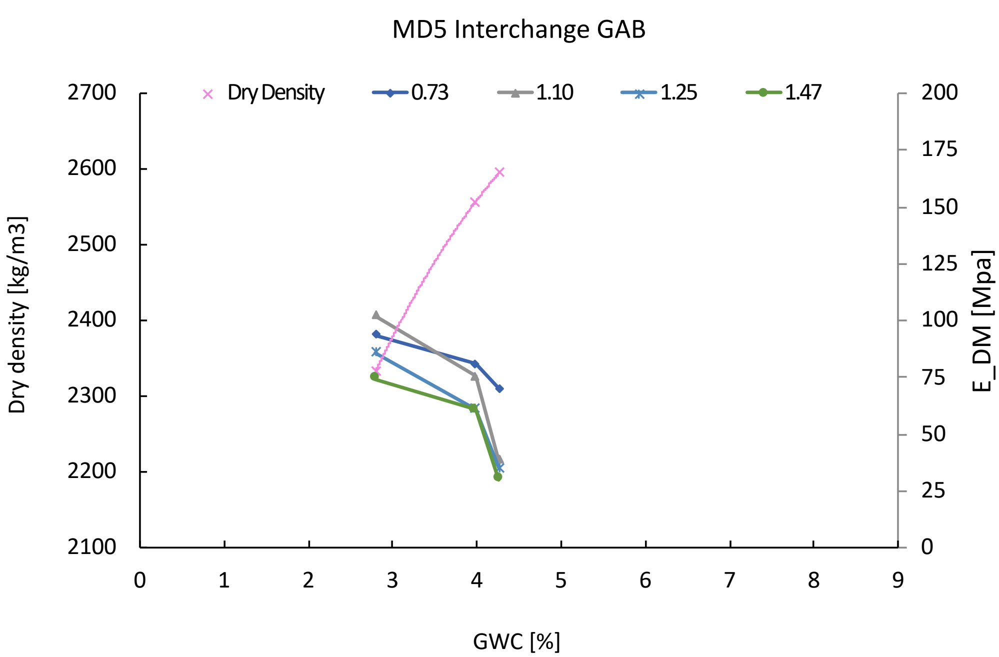



**Figure 71. Dynatest LWD modulus on mold superimposed on dry density versus GWC for MD5 Interchange GAB at variable P/Pa.**

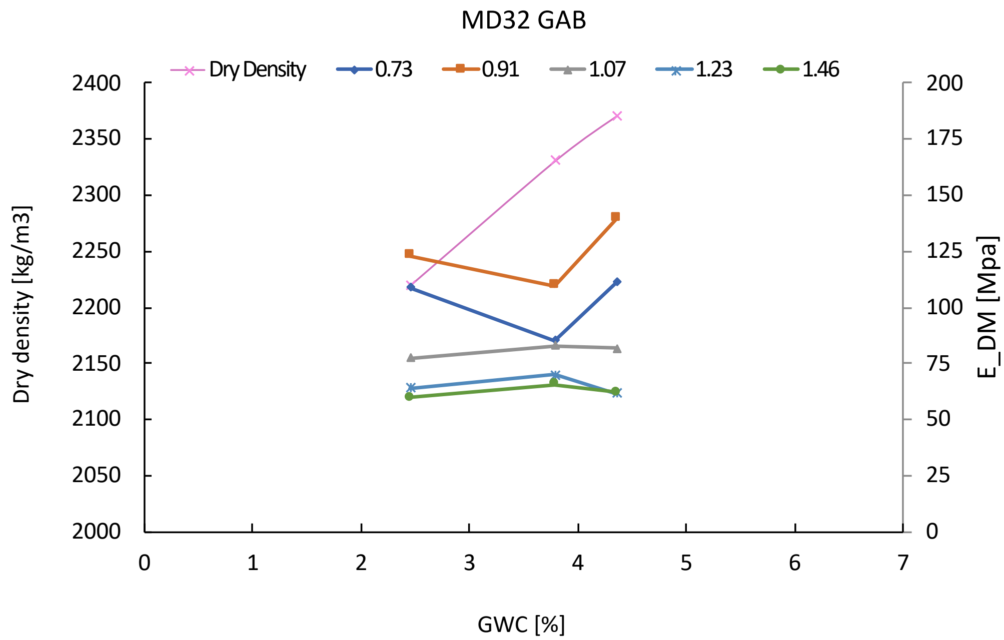



**Figure 72. Dynatest LWD modulus on mold superimposed on dry density versus GWC for MD32 GAB at variable P/Pa.**

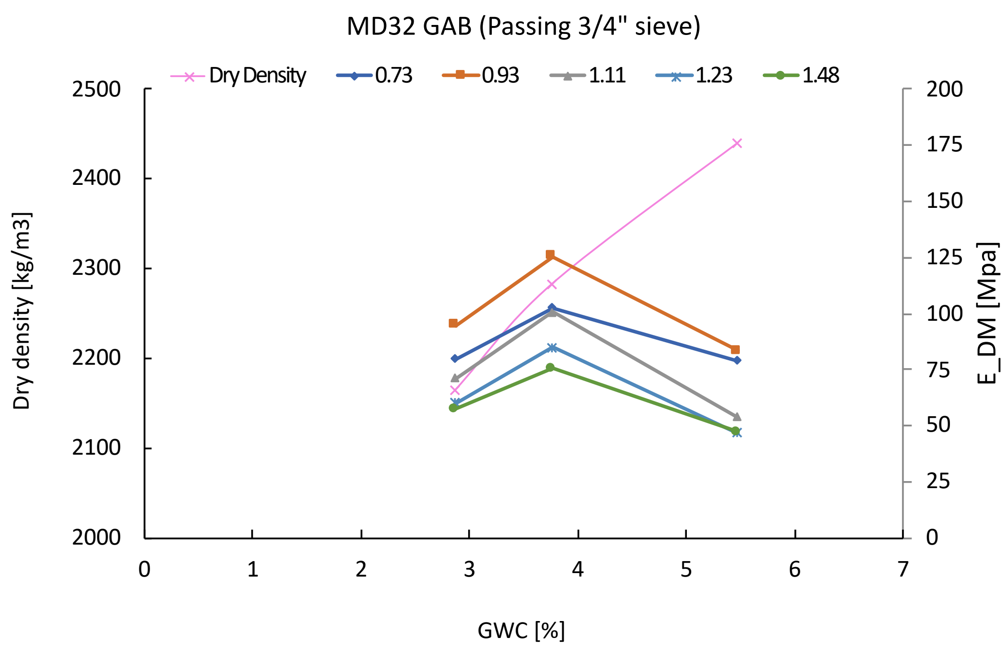



**Figure 73. Dynatest LWD modulus on mold superimposed on dry density versus GWC for MD32 GAB excluded oversized particles at variable P/Pa.**

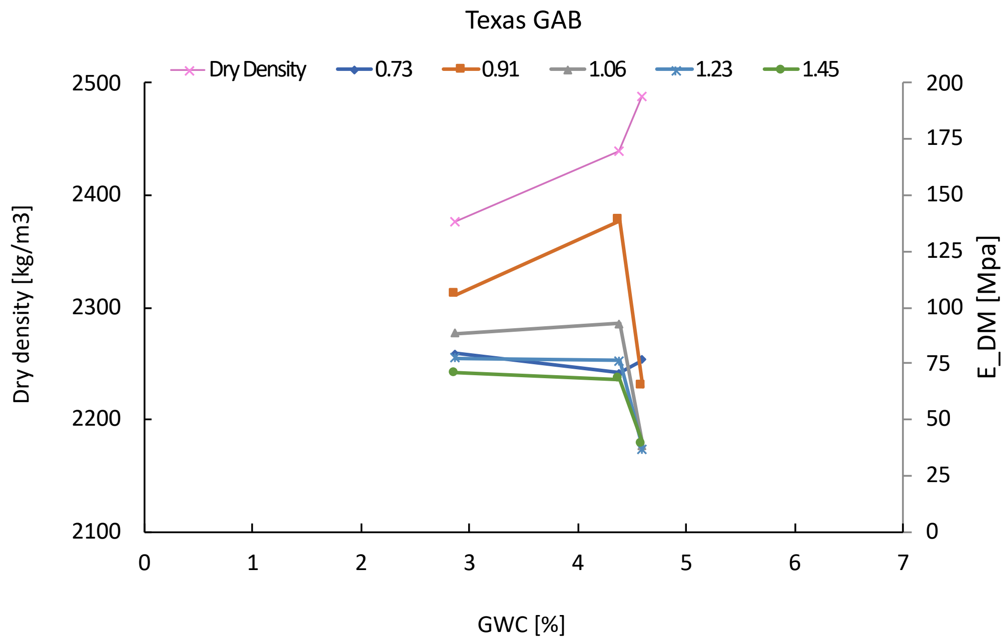



**Figure 74. Dynatest LWD modulus on mold superimposed on dry density versus GWC for Texas GAB at variable P/Pa.**

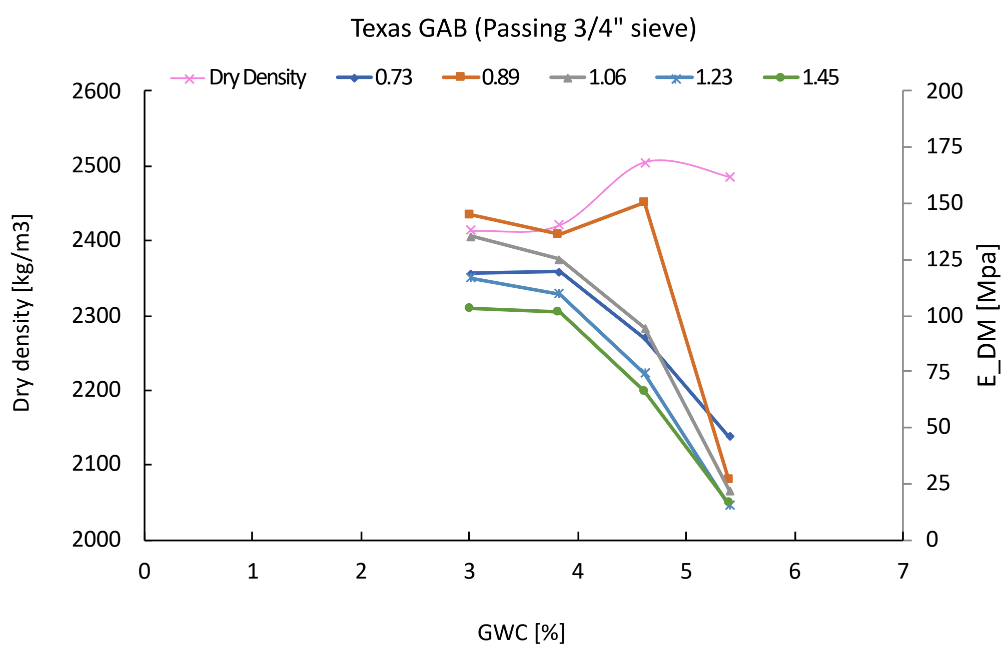



**Figure 75. Dynatest LWD modulus on mold superimposed on dry density versus GWC for Texas GAB excluded oversized particles at variable P/Pa.**

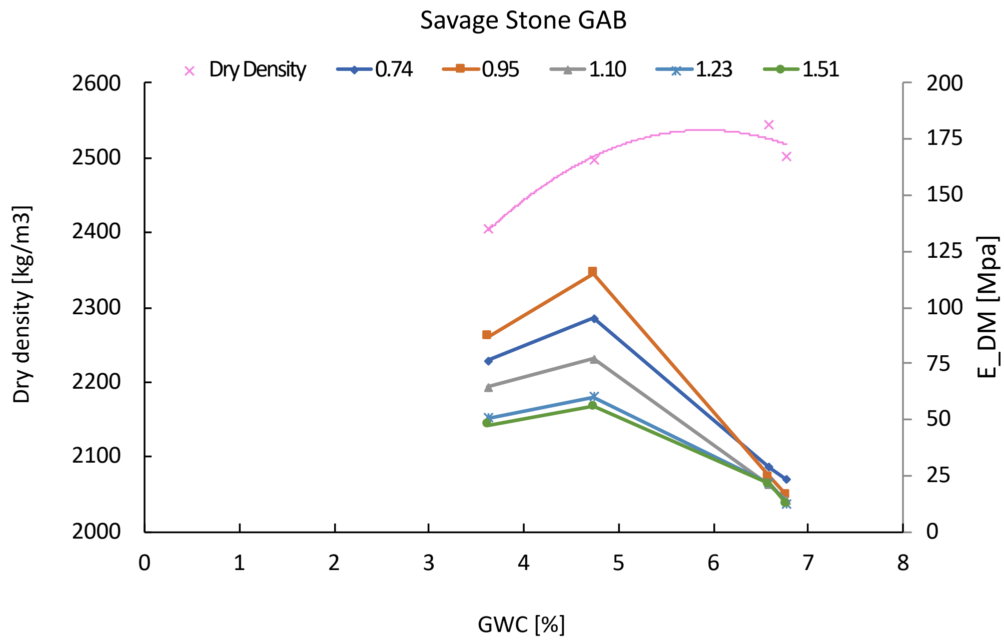



**Figure 76. Dynatest LWD modulus on mold superimposed on dry density versus GWC for Savage GAB at variable P/Pa.**

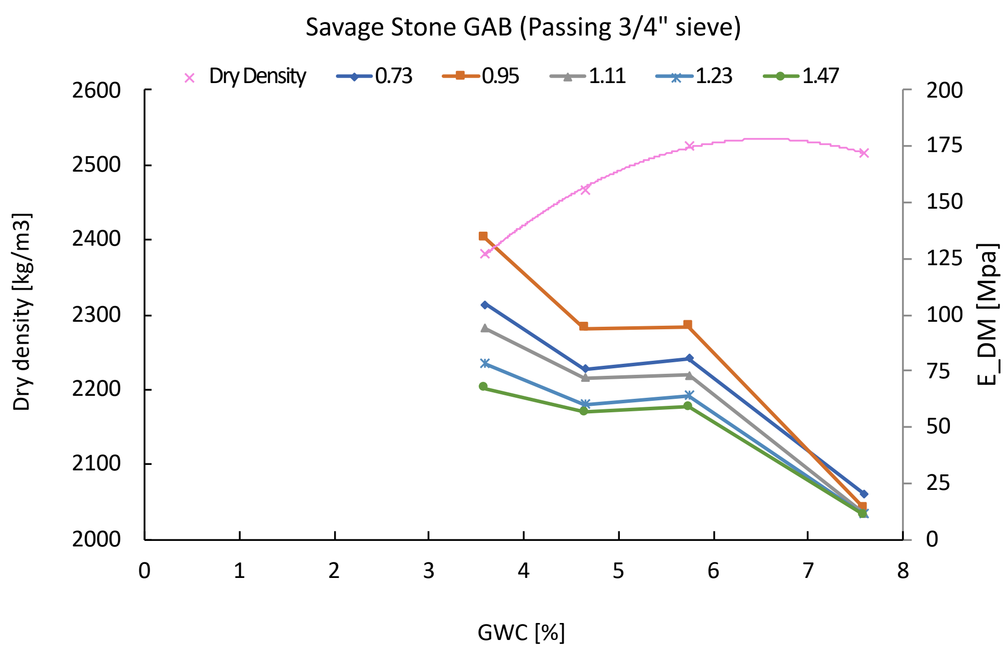



**Figure 77. Dynatest LWD modulus on mold superimposed on dry density versus GWC for Savage GAB excluded oversized particles at variable P/Pa.**

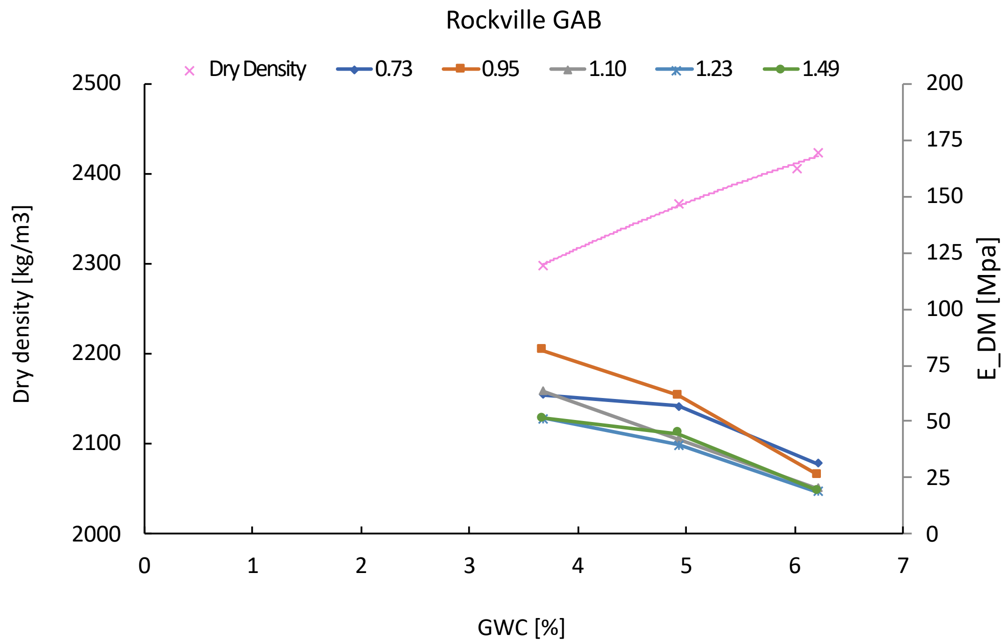



**Figure 78. Dynatest LWD modulus on mold superimposed on dry density versus GWC for Rockville GAB at variable P/Pa.**

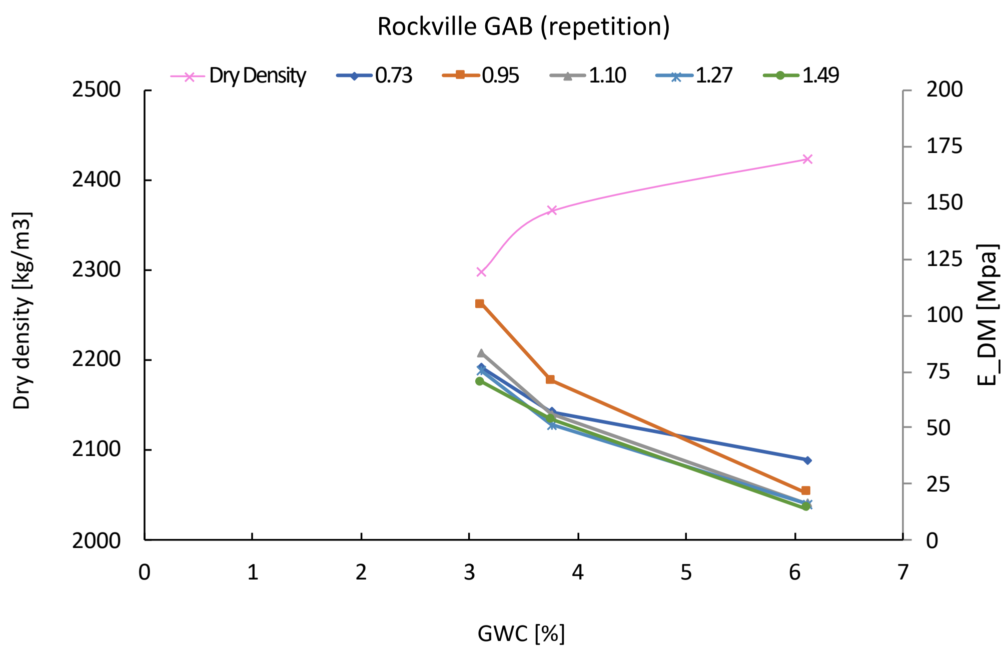



**Figure 79. Dynatest LWD modulus on mold superimposed on dry density versus GWC for Rockville GAB at variable P/Pa (repeated test).**

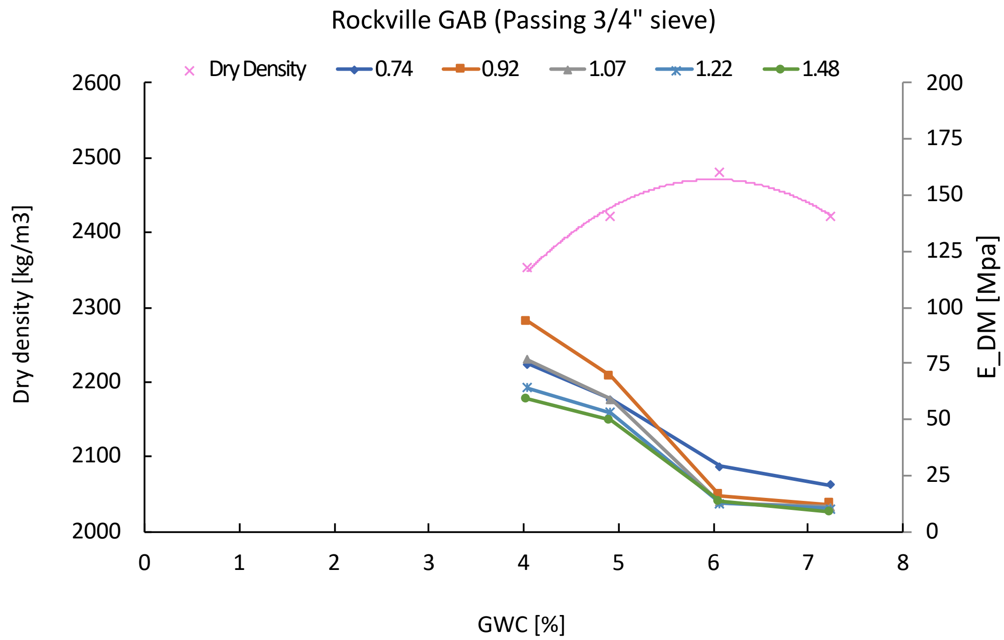


**Figure 80. Dynatest LWD modulus on mold superimposed on dry density versus GWC for Rockville GAB excluded oversized particles at variable P/Pa.**

### 6.3.3. *Comparisons of PC with Modulus Ratio*

Figure 81 presents the results of the PC versus $E_{field}/E_{target}$ for nine tested field sites.

The dashed blue line shows the MDOT SHA's minimum requirement of 97% PC for GAB compaction QA.

MDOT SHA requires compaction QA using NDG perform testing at one random spot per quarter lane-mile. The MC of the compacted geomaterial should be within 2 percent of OMC, and dry density should reach at least 97 percent of MDD. Therefore, MD5 ramp GAB and MD175 GAB were determined as acceptable quality even though variability exists in the PC in the adjacent testing spots.

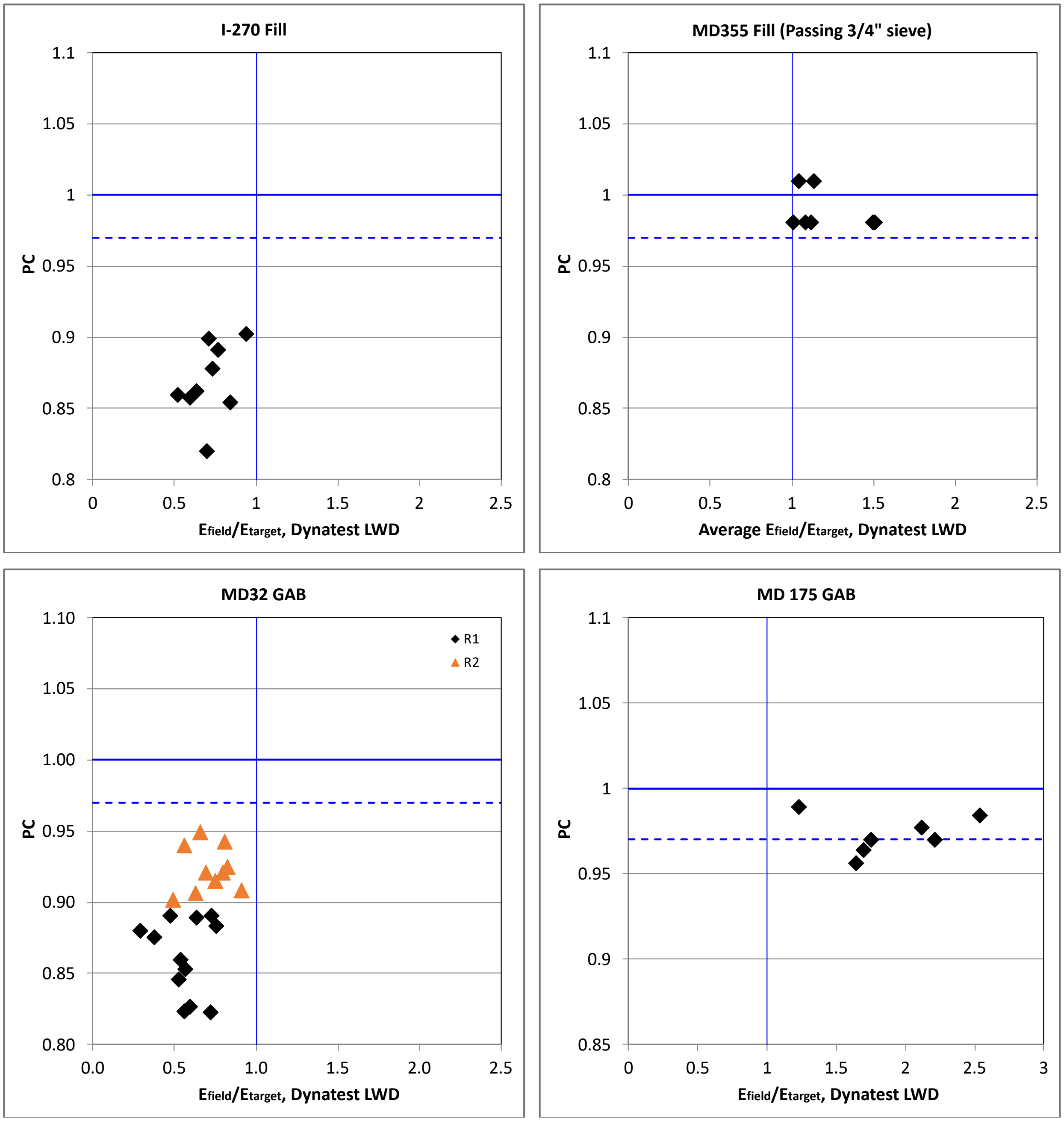



**Figure 81. PC versus field to modulus ratio**

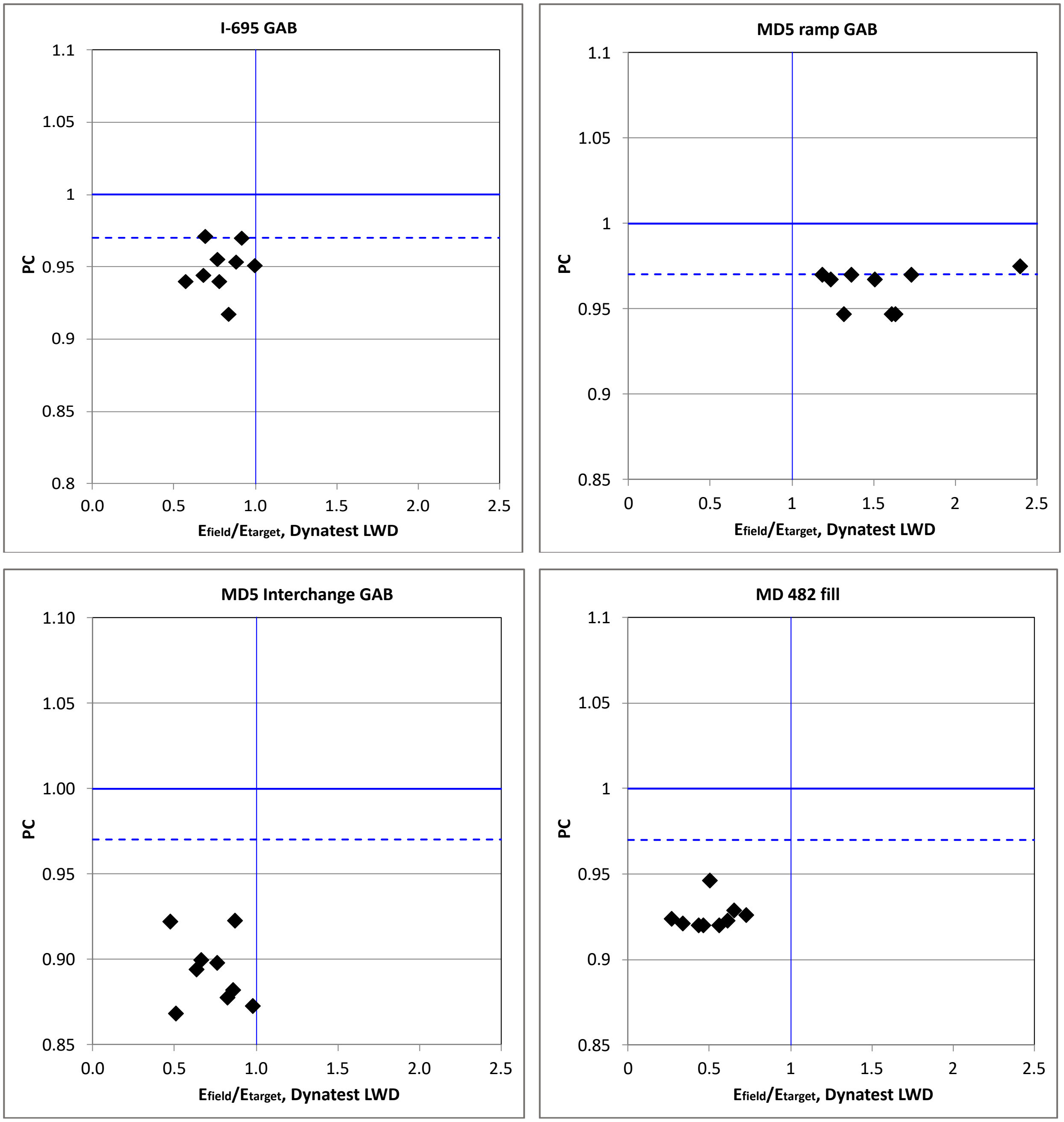


Figure 81 (continued).

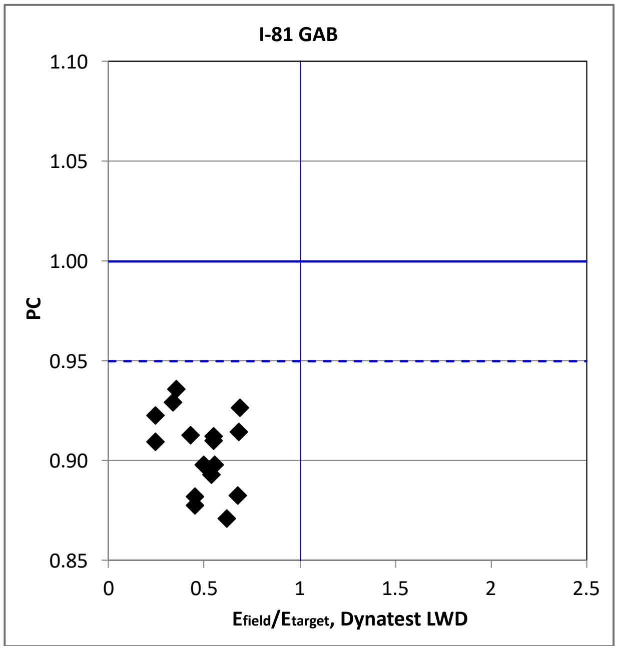


**Figure 81 (continued).**

To summarize:

- MD175 GAB, MD5 ramp GAB, and MD355 fill material passed both the PC and $E_{field}/E_{target}$ criteria.
- I-81 GAB, MD5 interchange GAB, I-695 GAB, MD32 GAB R1 & R2, I-270 fill and MD482 fill failed to meet both PC and $E_{field}/E_{target}$ criteria.

PC for these results is calculated based on the MDD from Proctor testing on the samples collected from the field. This confirms the validity of the procedure. If performed correctly, $E_{target}$ could be used to replace PC as a measure to assess the quality of compaction.

### 6.3.4. *Repeatability of the test procedure*

The repeatability of the LWD modulus on mold test values are an important consideration for any QA specification. Figure 82 and Figure 83 present the results for two replicate tests on two GABs: Texas and Rockville GABs. The LWD modulus on mold values are superimposed on Proctor curve and color coded for variable P/Pa. The solid lines represent results for the first replicate and the dashed lines for the second.

- GWC: gravimetric water content (MC)
- E_DM: Dynatest LWD modulus on Proctor mold
- Legend shows variable P/Pa (0.73, 0.89, up to 1.45) corresponding to different drop heights (1”,2”, up to 8”)

Table 26 presents the summary of repeated LWD on mold testing for Rockville and Texas GAB materials. Target modulus for both materials is calculated at their OMC and P/Pa of 0.94 for comparison.

**Table 26. Summary of repeatability testing results**

| Rockville GAB | Sample 1 | Sample 2 | %Difference |
|---|---|---|---|
| OMC [%] | 5.47 | 4.93 | 9.89 |
| MDD [kg/m$^3$] | 2386.08 | 2394.73 | 0.36 |
| Target E [MPa]* | 44.67 | 39.02 | 12.65 |

*Target calculate at P/Pa=0.94

| Texas/I-695 GAB | Sample 1 | Sample 2 | %Difference |
|---|---|---|---|
| OMC [%] | 4.39 | 4.49 | 2.28 |
| MDD [kg/m$^3$] | 2495.68 | 2463.32 | 1.30 |
| Target E [ksf]* | 87.67 | 83.74 | 4.48 |

*Target calculate at P/Pa=0.94

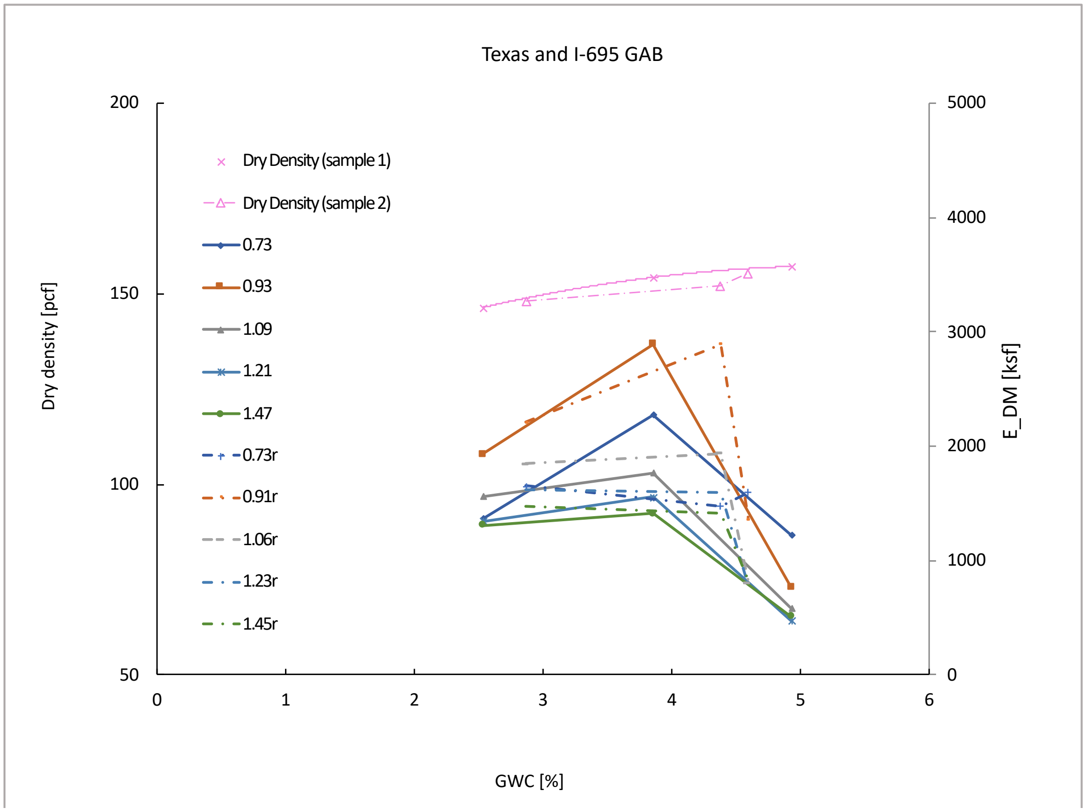



**Figure 82. Repeatability of LWD on mold testing (Texas GAB)**

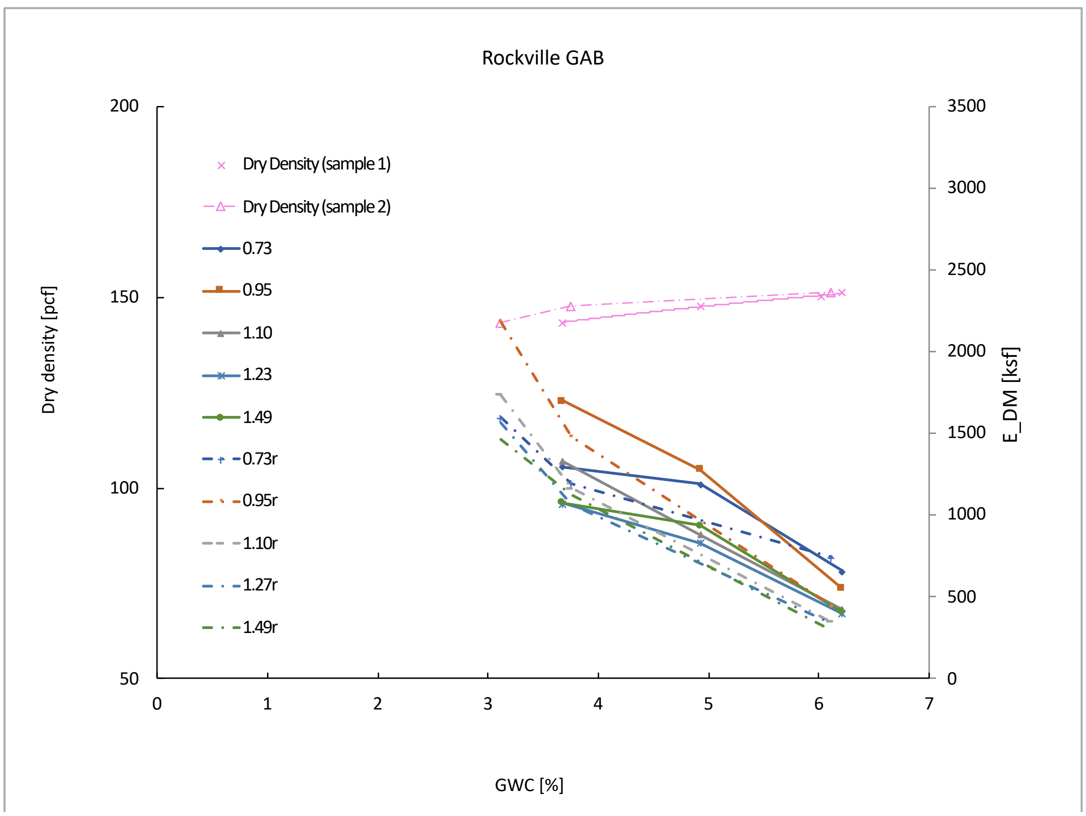



**Figure 83. Repeatability of LWD on mold testing (Rockville GAB)**

### 6.3.5. *Issues with Proctor mold compaction*

Some important lessons were learned from determining the moisture-density relationship in the lab by Proctor testing (AASHTO T180):

- Reusing the same sample of soil for each moisture content in the Proctor compaction test must be done with caution. According to AASHTO T-180 Section 5.4.1, fragile soils will be damaged by repeated compaction, resulting in progressively finer gradations. A separate new sample should be used for each moisture content.
- Most importantly, the compaction test should be continued by adding increments of water until there is either a decrease or no change in the wet mass per unit volume of the soil (AASHTO T-180, section 5.4). Using free water drainage from the bottom of the mold as a sign to stop the test can be subjective and lead to errors.
- Other factors such as material sampling and type of curve (e.g., parabolic vs. cubic) fitted to the data to find the extremum points can also contribute to errors.

Figure 84 presents the results for changes in gradation after reusing the soil sample in the Proctor testing. The percent retained on coarser sieve sizes consistently decreased and the percent retained on the finer sieve sizes consistently increased when the soil samples were reused. The percent retained on individual sieves changed by up to 10 percentage points after repeated compaction. In general, Proctor test should simulate the field compaction condition. Reuse of soil samples in the Proctor test does not match field conditions. Agencies using density-based compaction QA should consider this effect on the MDD.

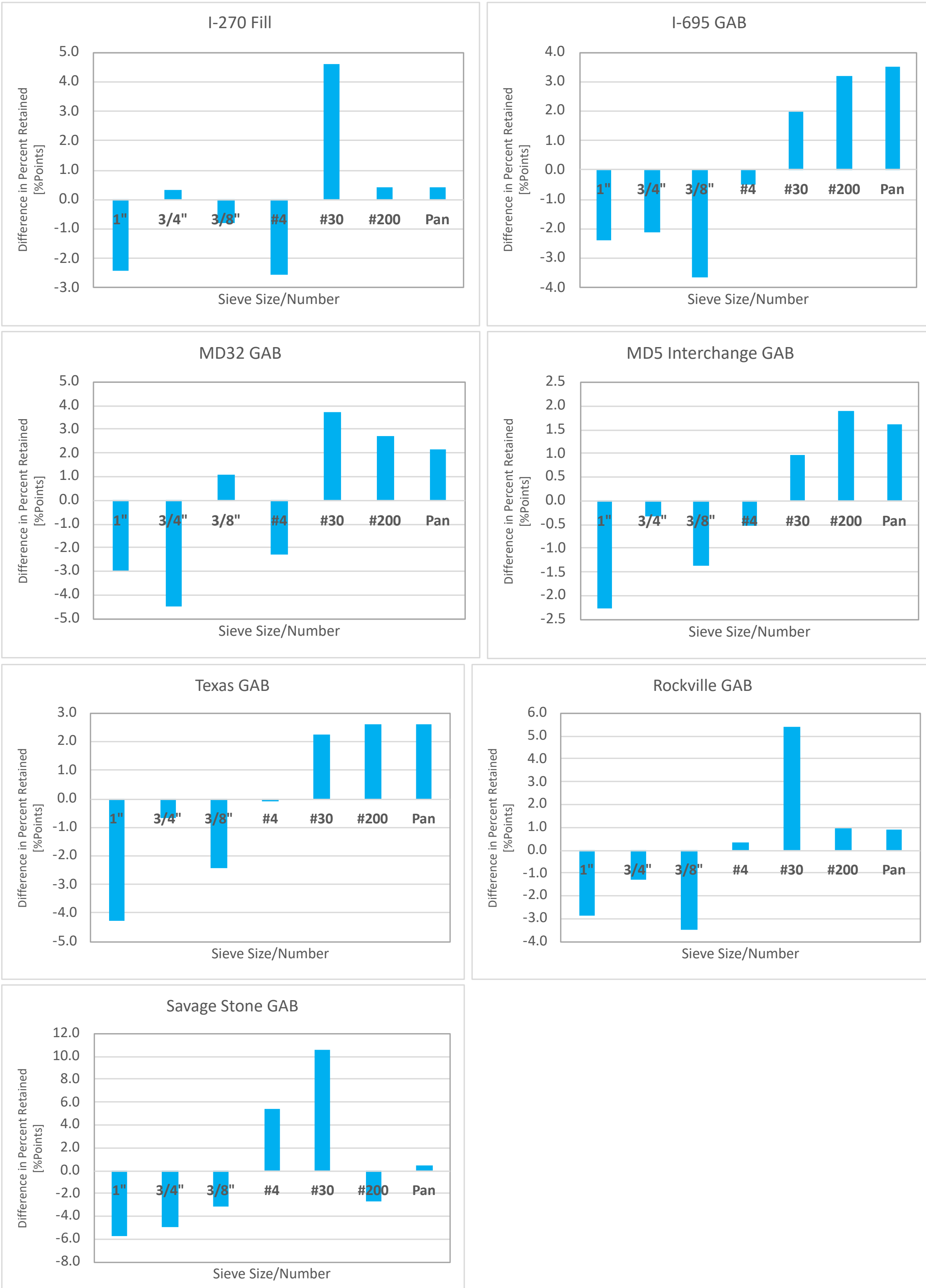



**Figure 84. Changes in percent retained on sieves after reuse of soil in Proctor compaction testing.**

### 6.3.6. ***Effect of plate size and plug***

Two important variations in LWD testing using the Dynatest device are the plate size and annular plug. The effects of these variations on the LWD measurements in the field were evaluated. LWD moduli were measured using an 200 mm (8 in.) diameter plate and compared to the moduli measure using the standard 300 mm (12 in.) diameter loading plate.

For the 300 mm diameter plate, the deflection measurements on the plate (with plug in) were compared to center rod deflection measurements (no plug--directly top of the soil).

Due to the limited time and tight construction schedule, only three test sites for two projects provided the opportunity of performing extra LWD testing: the MD5 interchange construction and the MD32 widening project for two different sections on two days (R1 and R2).

Comparing the regression coefficients from Figure 85 and Figure 86, it could be concluded that there is no single correlation for plate size or deflection measurement type and it changes depending on the soil, MC, PC, and construction circumstances.

In order to avoid discrepancies between laboratory and field LWD testing, it is recommended that the field LWD deflection measurement configuration be similar to the laboratory setup. If the LWD plate size is changed, the field pressure should be matched to the appropriate laboratory pressure when determining the target modulus (refer to Section 6.2.3).

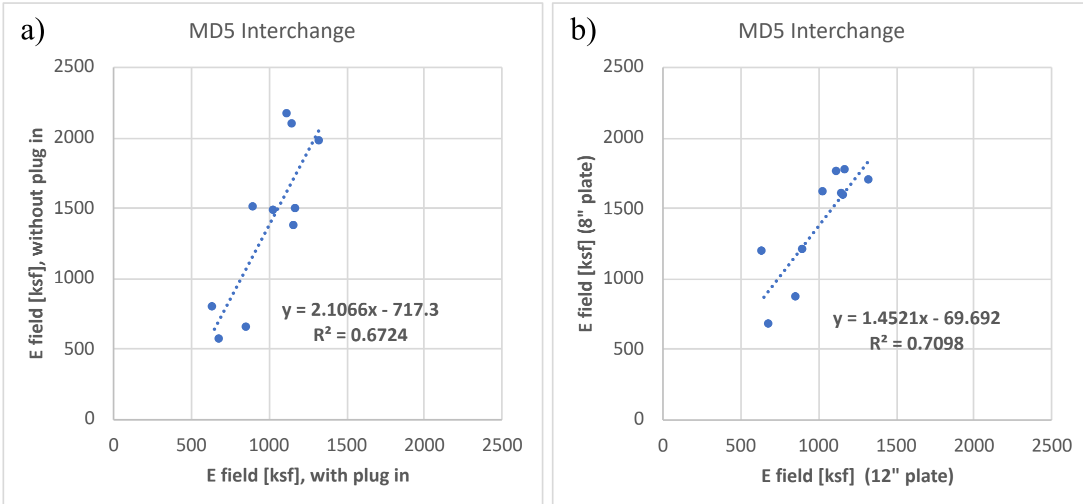



**Figure 85. Correlation of: (a) LWD modulus with and without the plug in; (b) 8 inch plate size vs. 12 inch plate size.**

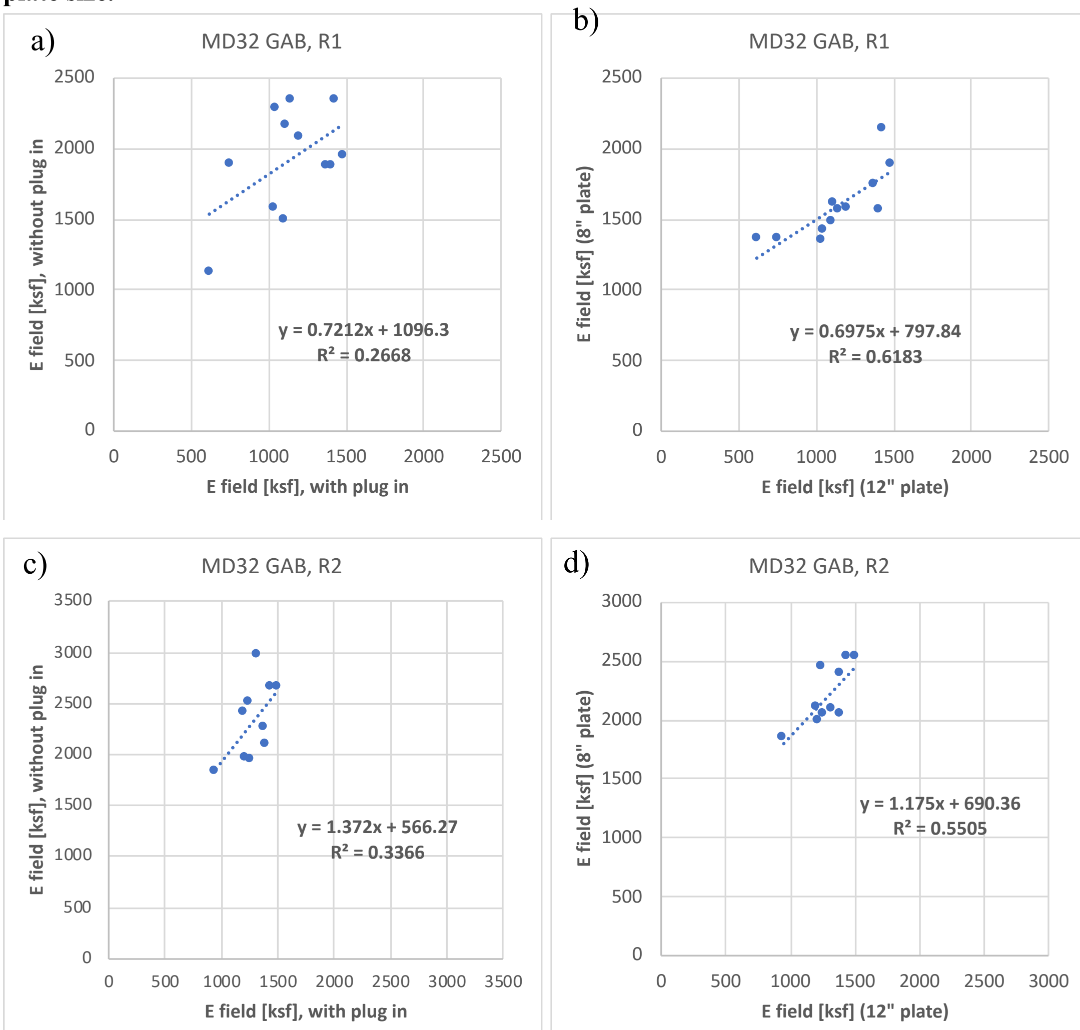



**Figure 86. Correlation of: (a,c) LWD modulus with and without the plugin; (b,d) 8 inch plate size vs. 12 inch plate size for first (R1)and second rounds of testing (R2).**

### 6.3.7. *Correction factor for excluding oversized particles in the mold*

The effect of scalping oversize particles (those retained on or above the ¾" sieve) on the target modulus from the LWD modulus on mold method was investigated for a subset of GABs. Table 27 lists the soils tested and the percentages retained on the 1.5 in. (38.1 mm) and ¾ in. (19.05 mm) size sieves. All target moduli were evaluated at OMC and P/Pa equal to 0.94.

The target E values evaluate for the molds compacted with original gradation soil are plotted in Figure 87 against the target E for molds compacted after scalping off ¾" and larger material. The data suggest that a quadratic empirical correlation can be used as a correction factor (scenario 1).

However, Figure 88 shows that if the two Texas GABs (Texas GAB and I-695 GAB from the same quarry) are excluded, the correlation falls on the line of equality, implying that excluding oversize particles does not affect the target E significantly (scenario 2). Consequently, additional testing for a wider range of soil types is recommend for the future in order to develop a better understanding of this effect.

**Table 27. List of soils evaluated for the effect of excluding oversize particles on the LWD on mold target modulus values.**

| Soil type | %Retained on 1.5" sieve | %Retained on 3/4" sieve |
|---|---|---|
| I-81GAB | 0.00% | 18.25% |
| Texas GAB | 1.82% | 20.35% |
| MD175 GAB | 0.00% | 8.50% |
| Savage GAB | 1.00% | 22.31% |
| Rockville GAB | 0.00% | 17.28% |
| MD5 ramp GAB | 0.00% | 21.35% |
| MD32 GAB | 3.62% | 22.84% |
| MD482 SG | 1.51% | 11.37% |
| I-695 GAB | 2.66% | 10.75% |

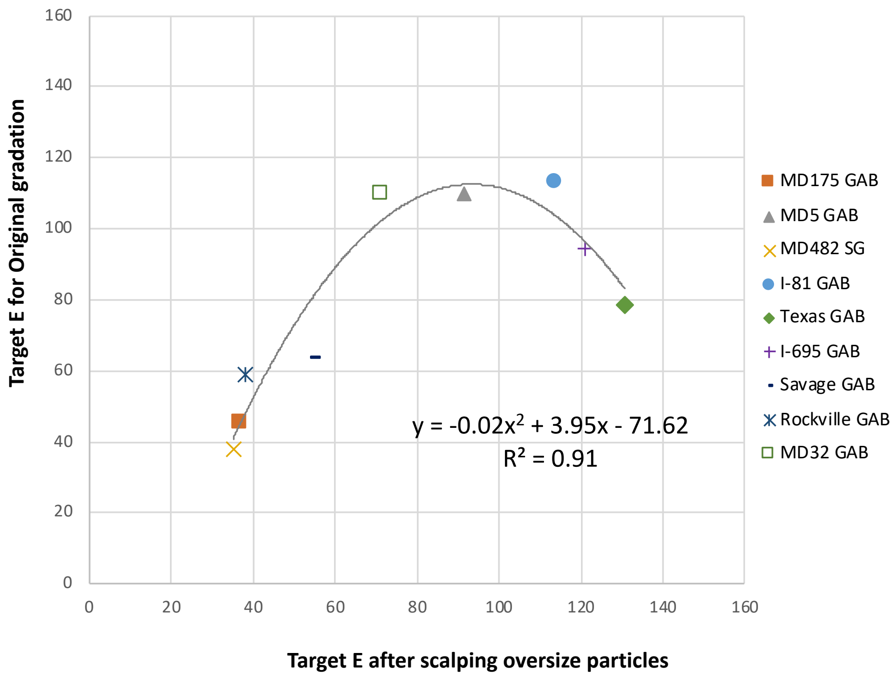



**Figure 87. Correction factor (scenario 1)**

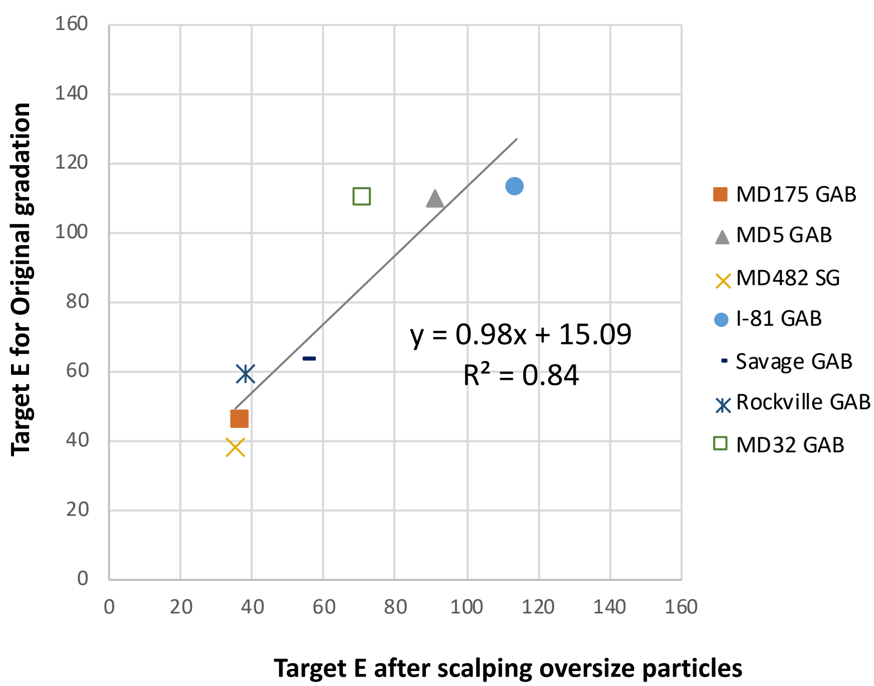



**Figure 88. Correction factor (scenario 2)**

## 6.4. Specification refinement and recommendations

The refinements to the LWD on mold and LWD in field test procedures are incorporated after the implementation study to the drafts in Appendix A. There are two acceptance criteria for good compaction: (1) Compaction MC must fall within an acceptable range around the OMC, and (2) The field-to-target modulus ratio must exceed the lower specification. The acceptable MC range for LWD-based compaction QA is set identical to that for current density-based compaction QA. The target LWD modulus must therefore be specified for that MC range.

In order for any new QA approach to be effective, the construction methods for unbound material construction must be refined and should include appropriate remedies to address compaction QA failures. These include:

- During material placement, the contractor must be careful to avoid segregation when spreading and grading.
- If compaction is delayed and the aggregate is stockpiled on the site for future placement, uniform distribution of moisture over the entire thickness for each lift must be achieved.
- The surface of each lift must be maintained until the next lift is placed.
- The roadbed (subgrade, subbase, fill) must be sufficiently compacted so that no rutting or displacement occurs when depositing additional materials on the road section.
- MC limits must be enforced as well as modulus (or PC in density-based methods) thresholds.
- MDOT SHA does not have any formal specification for using NDG in backscatter or direct transmission mode for GAB materials. Different project engineers or inspectors consequently perform the tests differently.

- When a random spot is tested and proved failing, the section must be reworked. Repeated testing to find another spot where a passing PC value is found is not acceptable.

### 6.4.1. ***Target LWD modulus***

Table 28 summarizes the GAB materials examined in implementation phase and their target LWD modulus values corresponding to the MDOT SHA's acceptable OMC range (values rounded up for easier use). All target moduli were calculated at P/Pa equal to 0.94, or a pressure of about 95.25 kPa (1990 ksf).

Note that the target E values for finite thickness base layers must be corrected for the subgrade/underlaying foundation's modulus using the method provided in Section 2.3.3. Figure 89 can be used in the field in lieu of calculations.

**Table 28. Target modulus values for tested GABs**

| # | Aggregate Source | Tested projects | OMC | Target E @OMC | Target E @OMC-2% | Target E @OMC+2% |
|---|---|---|---|---|---|---|
| | [-] | [-] | [%] | [Mpa] | [Mpa] | [Mpa] |
| 1 | Martin Marietta Materials, Pinesburg | I-81 | 4.4 | 125 | 115 | 70 |
| 2 | Martin Marietta Materials, Texas | I-695 | 4.6 | 75 | 95 | - |
| 3 | Aggregate Industries, Bladensburg | MD5 ramp | 4.3 | 100 | 175 | 75 |
| 4 | Aggregate Industries, Rockville | N/A | 4.9 | 60 | 90 | 25 |
| 5 | Savage Stone, Laurel | MD175 | 4.4 | 110 | 65 | 25 |
| 6 | Vulcan Materials Company, Fredrick | MD32 | 4.5 | 120 | 100 | 50 |

The symbols in Figure 89 are defined as follows:

$E_{surface}$ = target surface modulus to be achieved in field LWD testing

$E_1$ = modulus of the upper layer (e.g., GAB)

$E_2$ = modulus of the underlying layer (e.g., subgrade)

H = thickness of the upper layer

$r_0$ = radius of the LWD plate

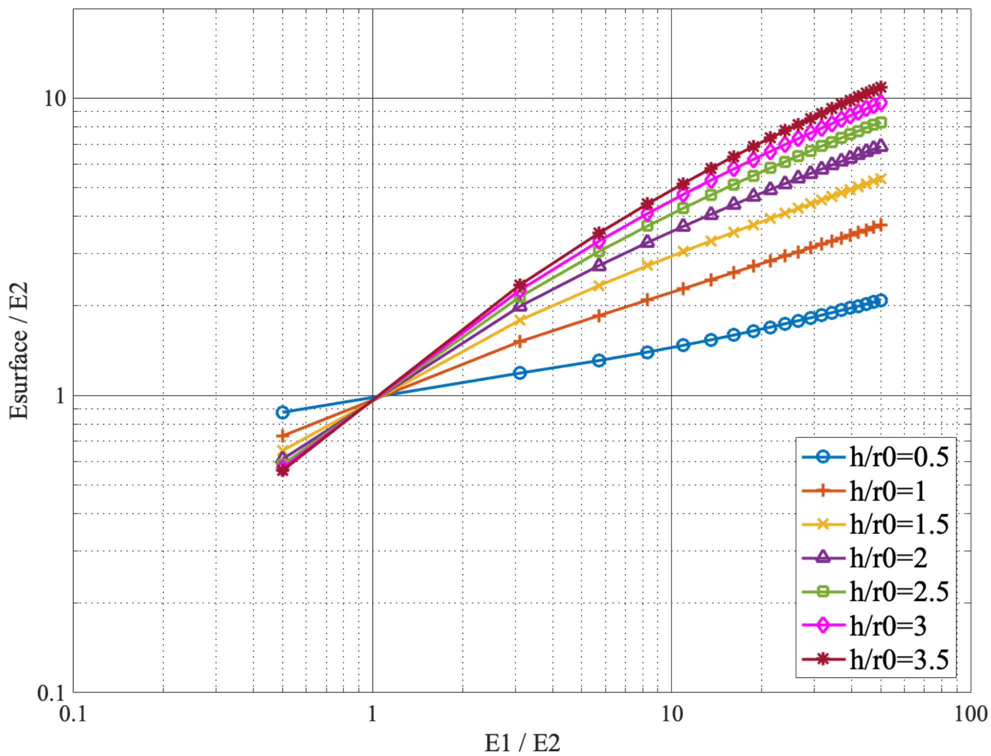



**Figure 89. Correcting target E for subgrade/underlaying layer effect**

### 6.4.2. *Acceptance Criteria and testing frequency*

Both LWD and NDG testing were performed at all of the field sites in order to provide guidance on selection of an appropriate lower specification limit (LSL) for $E_{field}/E_{target}$.

As is shown in Figure 90, all data points that satisfied the MDOT SHA PC specifation of 97% also had $E_{field}/E_{target}$ values greater than 1, as expected. Therefore, an LSL value of 1 is appropriate for QA compaction testing using the LWD.

Compaction should be rejected when an unacceptable number of $E_{field}/E_{target}$ values fall below the

LSL. Establishing what is an "unacceptable number" of failing $E_{field}/E_{target}$ values is an important part of the acceptance criteria. One approach for determining acceptance criteria is the percentage within specification limit (PWL) methodology (AASHTO R 9-05). This methodology is based on the quality index Q (Equation 12).

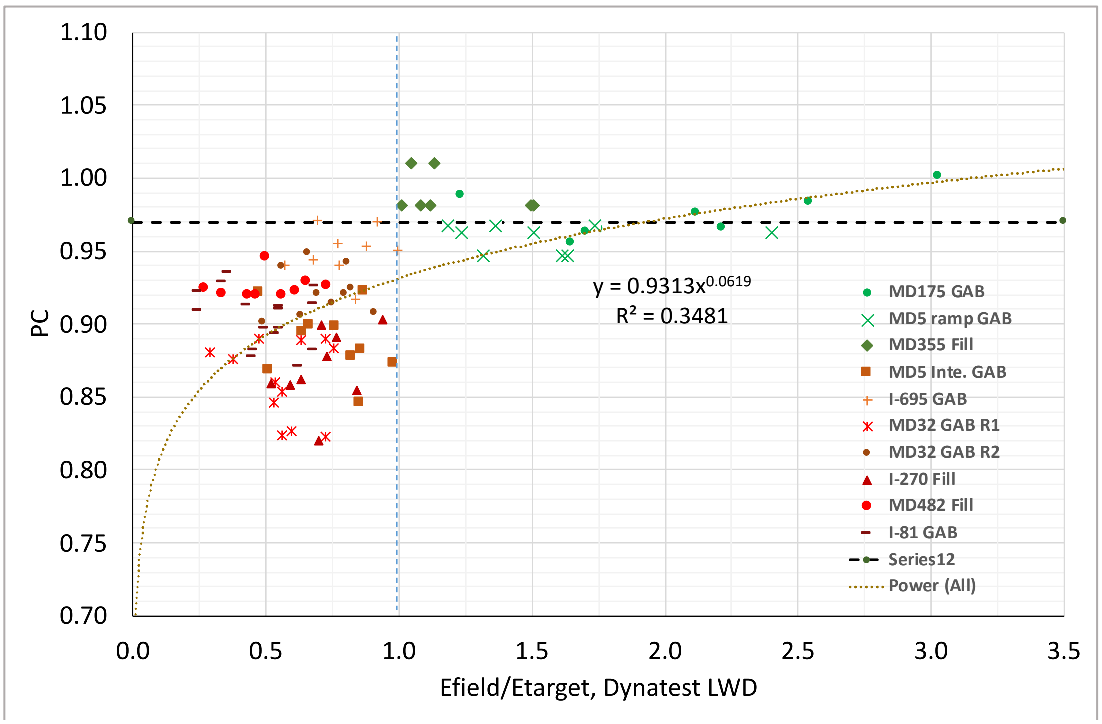



**Figure 90. Determination of lower limit for LWD field to target modulus**

The Q values for the projects evaluated in this study were calculated using the average and standard deviation of $E_{field}/ E_{target}$ for each project/material. These results are summarized in Table 29. The PWL is then obtained from a PWL estimation for the Q value and a given sample size.

Table 14 shows the table for determining PWL from the Q value for a sample size of 10.

To achieve a minimum acceptable PWL of 80%, sample size was altered and PWL was calculated for different Q values for the tested projects in this study, then compared to the 80% to find the minimum sample size. Consequently, a minimum sample size of 10 per quarter lane mile per lift is required to ensure capturing the acceptable PWL of 80% for well-compacted geomaterial. Here it is assumed that the SD of samples taken in this study is equal to SD of a quarter lane mile per lift.

For the limited number of well-compacted test sites evaluated in this study (green shaded cells in Table 29), the minimum PWL equals to 83%.

Appropriate remedial procedures should be adopted for lots with an estimated PWL less than the agency minimum. Removal and replacement, corrective action, or reduced pay factor are common remedial procedures.

**Table 29. PWL for the tested materials (green cells correspond to well-compacted materials, orange cells correspond to poorly compacted materials)**

| | $E_{field}/E_{target}$ | $E_{field}/E_{target}$ | LSL | Q | PWL |
|---|---|---|---|---|---|
| **Project** | **Avg [-]** | **SD [-]** | **[-]** | **[-]** | **[%]** |
| MD175 GAB | 2.03 | 0.57 | 1.0 | 1.81 | 97.60 |
| MD5 GAB | 1.55 | 0.37 | 1.0 | 1.50 | 94.13 |
| I-695 GAB | 0.79 | 0.13 | 1.0 | -1.58 | 4.79 |
| MD32 R1 | 0.56 | 0.14 | 1.0 | -3.13 | 0.00 |
| MD32 R2 | 0.71 | 0.13 | 1.0 | -2.22 | 0.39 |
| MD5 int GAB | 0.74 | 0.17 | 1.0 | -1.55 | 5.18 |
| I-81 GAB | 0.49 | 0.14 | 1.0 | -3.55 | 0.00 |
| MD482 fill | 0.51 | 0.15 | 1.0 | -3.31 | 0.00 |
| MD355 fill | 1.20 | 0.21 | 1.0 | 0.94 | 82.44 |
| I-270 fill | 0.72 | 0.13 | 1.0 | -2.23 | 0.37 |

A judgment must be made regarding what variability to use as the "typical" variability for determining the number of tests. According to AASHTO R 9-05, "the typical process variability should not be set for the most or least consistent contractor." This suggests that a typical within-lot variability value should be based on all of the values measured in this study rather than just the single best or worst project.

It is observed that the SD for each field test site tends to increase with the average modulus. Therefore, COV can be used to determine the typical variability. After sorting COV values from smallest to largest (Table 30), the median COV value of roughly 20% is chosen as the "typical" value for both GAB and fill materials, which is similar to ASTM E2583-07 (2011) Section 10.3. This corresponds to a median field modulus value of about 55 MPa. Projects with COV and/or field modulus values greater than these would have to reduce their variability to meet the specifications.

**Table 30. Range of SD and modulus in the field for GABs and fill material. Highlighted rows correspond to the median for each material type**

| | | LWD field modulus | | |
|---|---|---|---|---|
| # | **Project** | **Avg [MPa]** | **SD [MPa]** | **COV [%]** |
| 1 | I-695 GAB | 77.35 | 13.84 | 17.89 |
| 2 | MD32 GAB R2 | 67.16 | 12.03 | 17.91 |
| 3 | MD5 ramp GAB R1 | 159.50 | 30.33 | 19.02 |
| 4 | MD5 Int. GAB | 48.28 | 10.80 | 22.37 |
| 5 | MD32 GAB R1 | 54.55 | 12.74 | 23.35 |
| 6 | MD5 ramp GAB R2 | 163.63 | 38.89 | 23.77 |
| 7 | I-81 GAB | 62.56 | 15.14 | 24.2 |
| 8 | MD175 GAB R2 | 128.05 | 61.02 | 47.65 |
| 9 | MD175 GAB R1 | 112.10 | 57.31 | 51.12 |
| | **Minimum value** | 48.28 | 10.80 | 17.89 |
| | **Maximum value** | 163.63 | 61.02 | 51.12 |
| | **Average value** | 97.02 | 28.01 | 27.48 |

| | | | | |
|---|---|---|---|---|
| 1 | MD355 fill | 49.78 | 9.65 | 19.39 |
| 2 | I-270 fill | 50.70 | 10.21 | 20.14 |
| 3 | MD482 fill | 21.96 | 9.97 | 45.4 |
| | **Minimum value** | 21.96 | 9.65 | 19.39 |
| | **Maximum value** | 50.70 | 10.21 | 45.4 |
| | **Average value** | 40.81 | 9.94 | 28.31 |

# 7. Chapter 7: Recent Developments in LWD Devices

Following the methodology investigated in this study and in collaboration with the researcher, Dynatest LWD developed a new application to facilitate the modulus-based compaction QA in the field. The LWD 3032 app has a user-friendly interface that is available on both IOS and Android. The main features of the app are presented in this chapter. Please refer to Dynatest LWD manual for further details.

The app enables using $E_{target}$ from LWD on mold or target deflection as the QA criterion. The user can input plate diameter, number of geophones and their radial distance in the app's mechanical tab. The Poisson's ratio for field or lab testing, stress distribution factor under the LWD plate in the field depending on the geomaterial type and relative stiffness, and mold's height is inputted into the calculation tab (Figure 91).

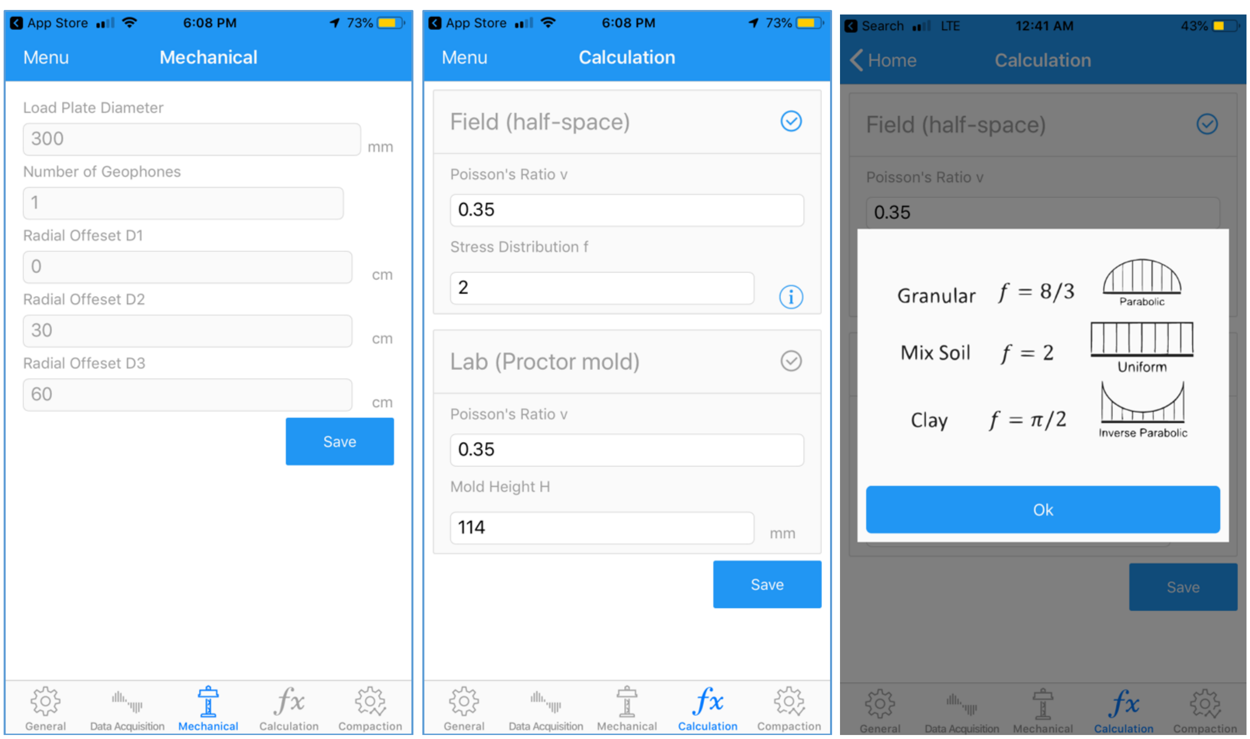


**Figure 91. Dynatest LWD iPhone app: mechanical input, and calculation input tabs.**

The operator can select the QA criteria in the Compaction tab (Figure 92). Three types of criteria are available: (1) field to target modulus or E/TargetE in the app ( same as $E_{field}/E_{target}$), (2) field to target deflection at a certain pressure or $D_1$@P/Target$D_1$ in the app, and (3) percentage deflection change or delta deflection. The user can enter the target and acceptance %value for one-layer system. The app can also correct the target modulus for layered structures by inputting the thickness of the overlain layer and modulus of sublayer.

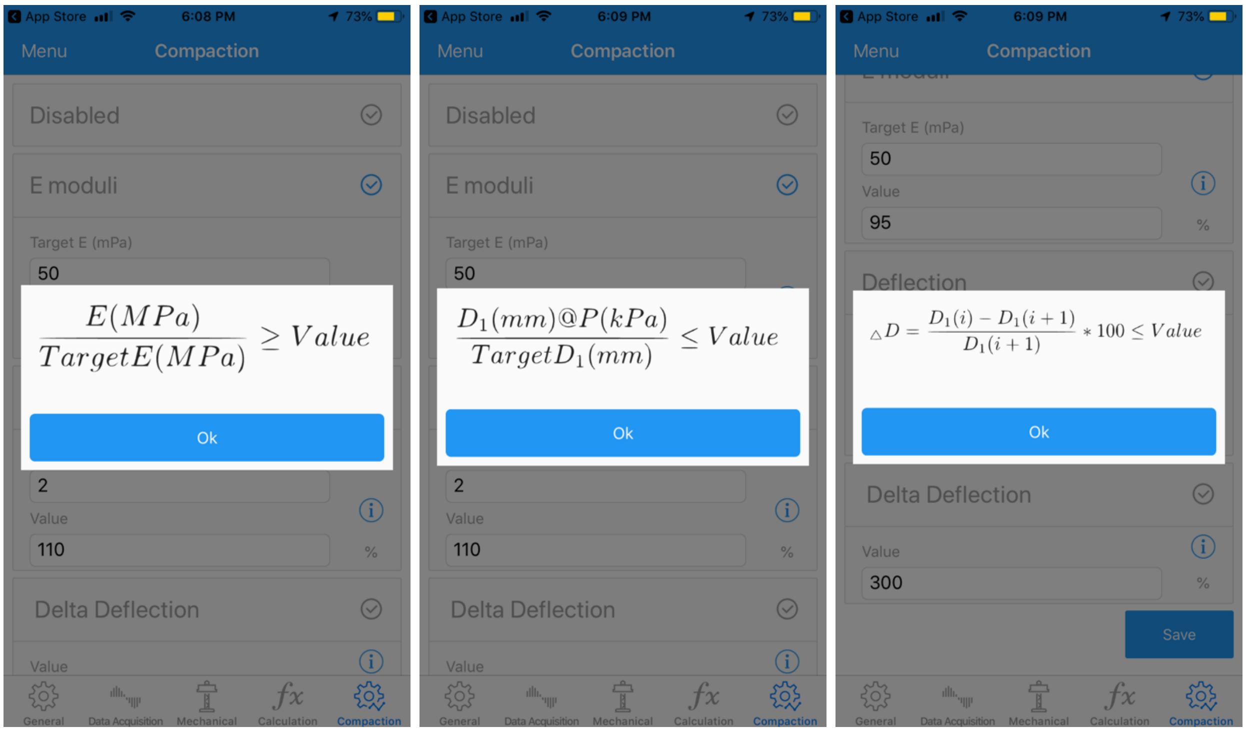


**Figure 92. Dynatest LWD iPhone app: three QA criteria available for compaction evaluation.**

The app reads the project location's coordinates using cellphone GPS and has the ability to take and store pictures of testing locations. The operator can enter the soil MC, date, and temperature data prior to testing at a location (Figure 93). After performing the LWD drops, QA evaluation shows passing or failing compaction and load/deflection signals in real time. All of the measurements, notes and pictures are stored and can be retrieved in tabular format using Dynatest software, *LWDmod*.

Test summary shows the number of drops on each spot, average modulus, and average deflection of the drops (Figure 94). Project summary exhibits number of testing sessions if tests were performed on multiple sessions on a project, number of tested locations, average modulus and deflection of the locations, and a visualization of number of passing versus failing spots.

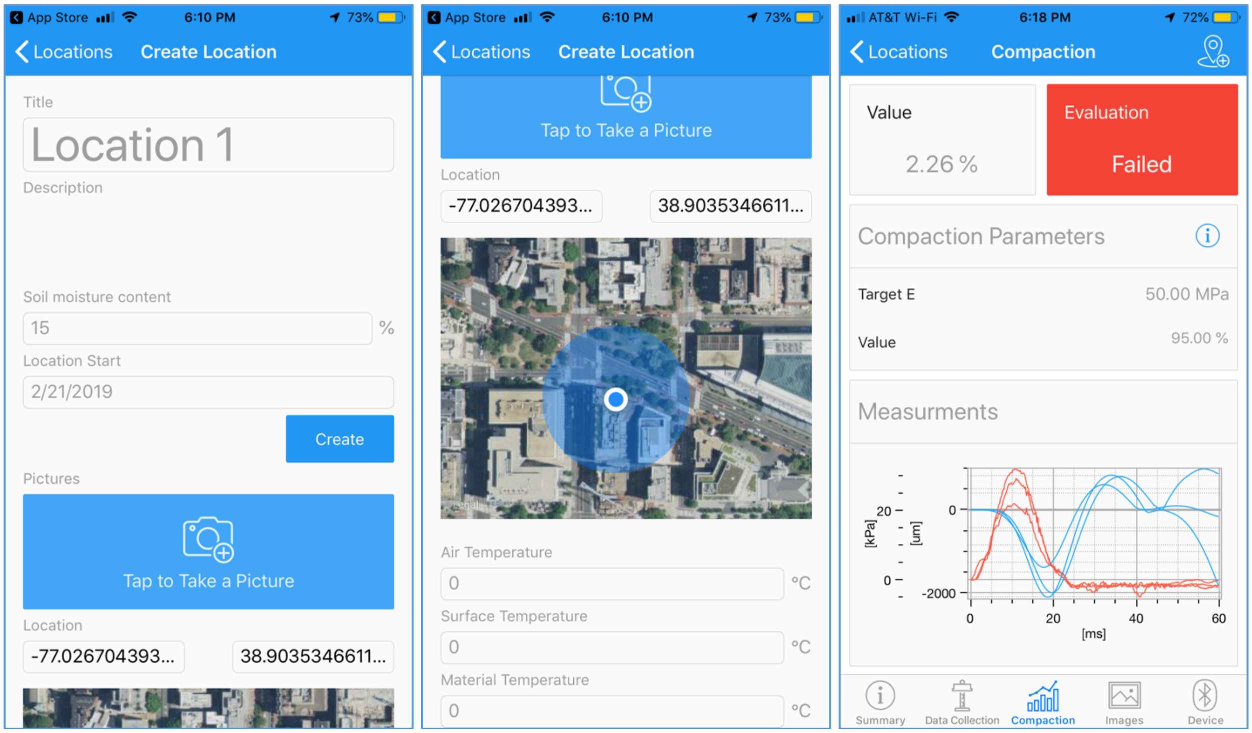


Figure 93. Dynatest LWD iPhone app: GPS location, %MC input, and spot test evaluation.

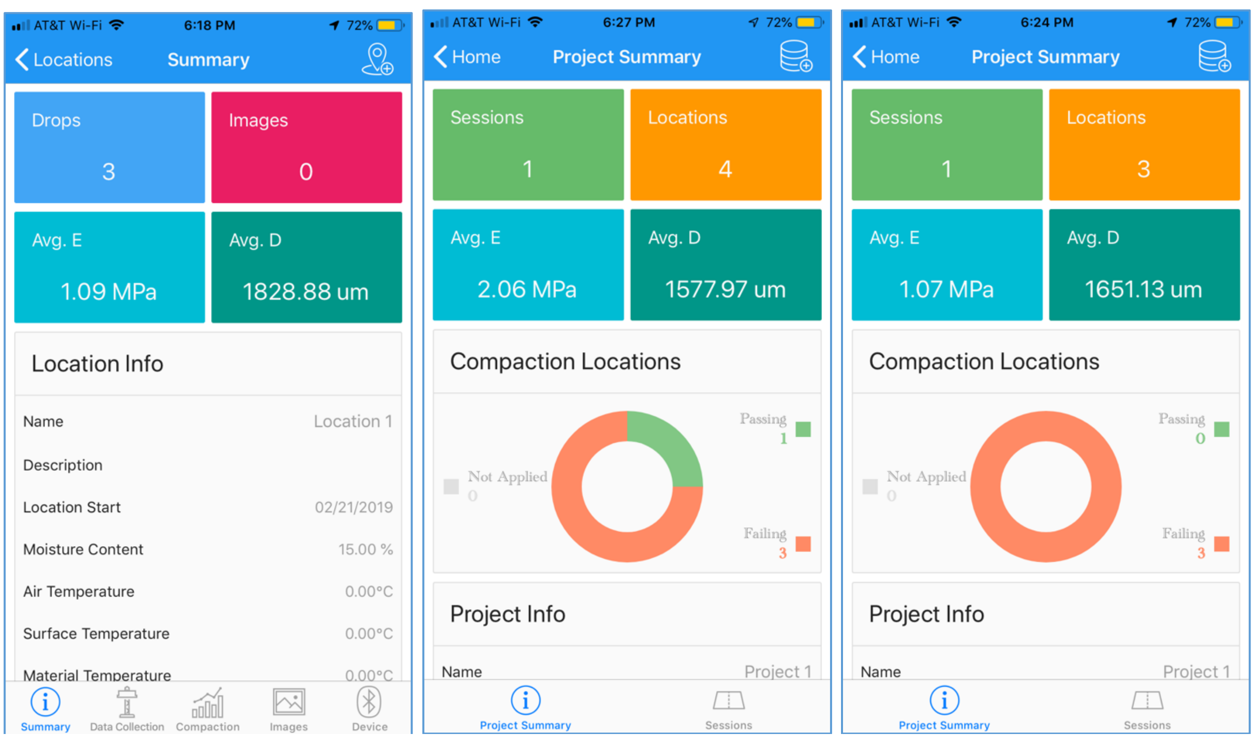


Figure 94. Dynatest LWD iPhone app: project summary tab including number of drops, average modulus,

**average deflection, and compaction location assessment.**

Olson Instruments designed the laboratory LWD unit, that is a shorter apparatus with a lighter weight (3.6 kg / 4 lbs) to match loading pressure and impulse duration time in proctor molds for soil target determination to in-situ field testing (Figure 95).


**Figure 95. Olson LWD-Lab unit ready to test a sample in Proctor mold ( Link to picture source)**

Olson Instruments also developed a software application for their data receiver, the Dell™ sunlight viewable tablet with GPS, called *WinLWD*. This software provides force, displacement, stiffness, and modulus values in real time during field and laboratory testing (Figure 96). The user can input the number of drops, Poisson's ratio, MC, density of the mold, plate diameter, and stress distribution factor ("soil type" in the software).

When the density and MC of Proctor molds are available, they can be imported to *WinLWD* and displayed to find the acceptable target based on the MC range (Figure 97).

Figure 96. Olson WinLWD software for field and laboratory testing

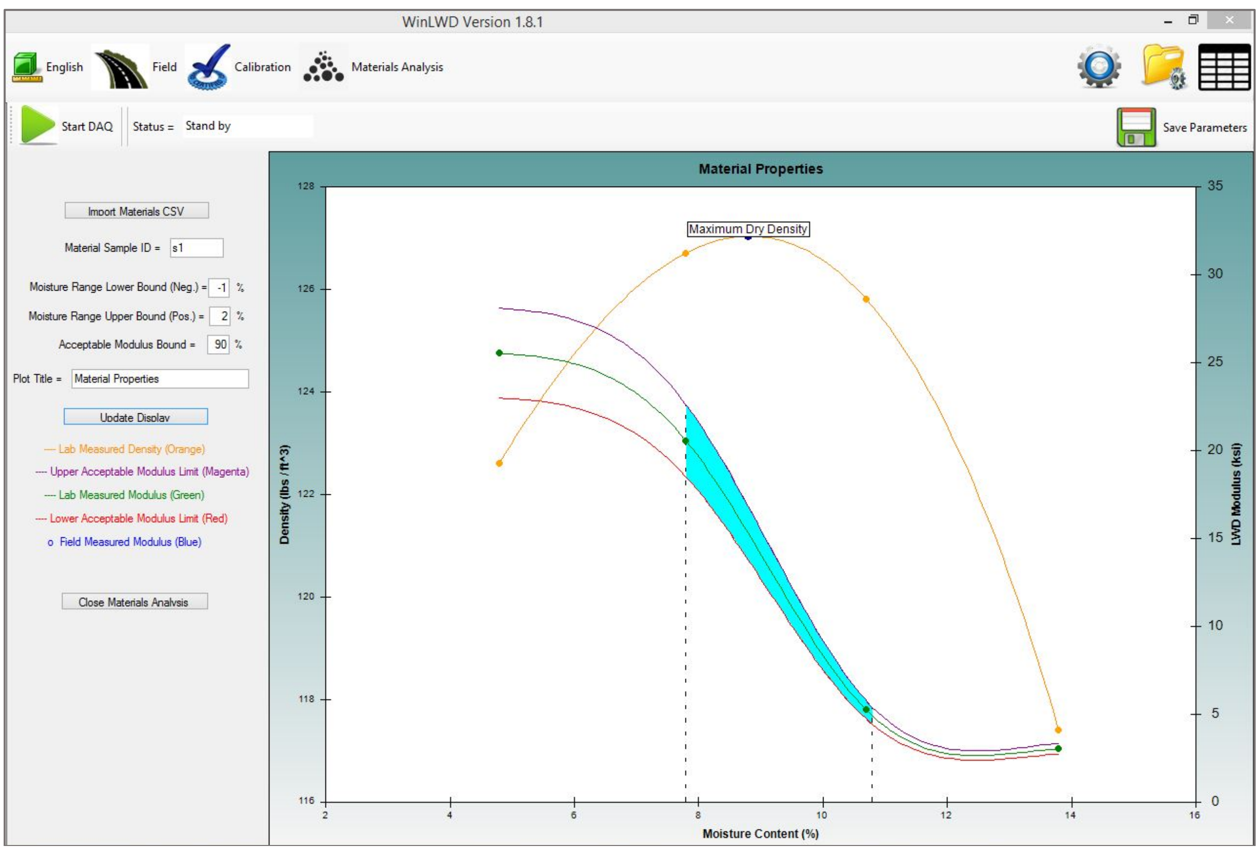


Figure 97. Density and MC from Proctor mold entered in the WinLWD.

Zorn instruments designed the laboratory LWD prototype which is adopted from the field test LWD version (Figure 98). The drop height is 37.5 cm with a 5 kg falling weight and 106 N/m spring constant that generates a 5.54 impact force. A shorter collar is used after mold preparation to keep the LWD plate in place and clear of the mold's rim, similar to the one used during the TPF-05(285) pooled fund study.

Figure 98 exhibits the testing and data collection procedure as described by the Zorn's Laboratory LWD manual.

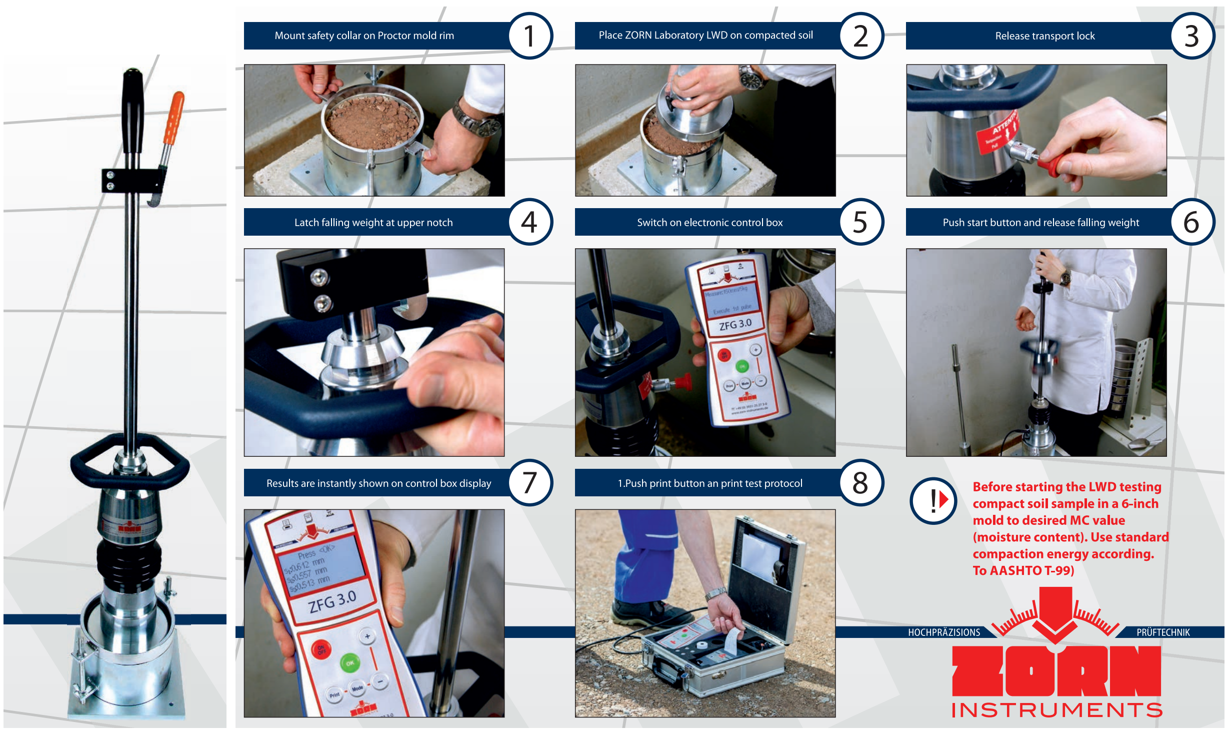



**Figure 98. Prototype of Zorn lab LWD and testing on mold procedure (Link to the pictures source)**

# 8. Chapter 8: Conclusions and Future Studies

This dissertation is based on two research projects: (1) Transportation Pooled Fund Study TPF-05(285) and, (2) Implementation of LWD for Modulus-Based Compaction QA of Unbound Materials in the State of Maryland. Three LWD brands were employed in these studies: Zorn ZFG3000, Olson LWD-01, and Dynatest 3031 LWD. These span the range of configurations available in commercial LWD devices.

Modulus-based quality assurance (QA) approaches are gaining attention in the pavement industry as conventional nuclear density gauge (NDG) testing becomes less attractive due to safety, regulatory, and cost concerns. LWDs are already in use for this purpose in some states and countries.

The pooled fund study started with an extensive review on the current LWD-based compaction QA in practice at different DOTs and worldwide. Approaches implemented by Minnesota, Indiana, Florida, Nebraska were studied in addition to those used by the European Union and United Kingdom. These agencies generally used: (1) calibration of target deflections using a test section or calibration area, (2) correlations with resilient modulus testing, (3) correlation of LWD deflections with DCP penetration or other in situ testing techniques, and (4) successive LWD drops on the loose, non-compacted material at the site to find the target LWD deflection or modulus values.

Nearly all existing approaches for compaction QA using LWDs are based on <u>deflections</u>, not modulus. Practical implementation of a <u>modulus</u>-based QA requires two main elements: (1) a procedure for determining the target modulus for a given soil in the laboratory; and (2) a protocol for measuring the in-place LWD modulus in the field.

The innovative approach developed in the present research for determining the target modulus is LWD testing directly on the Proctor mold in the laboratory. This is an easy add-on to the conventional Proctor test (AASHTO T-99 and T-180).

The Proctor molds were compacted at various moisture contents using standard or modified Proctor energy. LWD deflections and moduli from multiple drop heights were captured. The formula for determining modulus from LWD on mold testing was derived from the linearly elastic stress-strain relationship of an axially symmetric and laterally constrained Proctor mold under LWD loading.

The field-to-modulus-ratio ($E_{field}/E_{target}$) was used as a criterion to assess the quality of compaction. This approach eliminates the need to match different LWDs measurements, when using the same type/brand of device for target determination in lab and moduli measurement in the field. Target moduli were extrapolated at the corresponding field water content and plate pressure and compared to measured moduli in the field to calculate $E_{field}/E_{target}$.

Moisture content is a critical factor affecting the modulus of compacted geomaterial in the field and must be measured along with LWD testing. The Ohaus moisture analyzer was selected for field determination of moisture content. Evaluation fo the Ohaus moisture analyzer against NDG and oven drying methods found acceptable correlation. However, it is recommended to use the new Ohaus device models with higher soil capacity to test larger aggregates in the field.

A total of eight projects in six states were visited during the field validation phase of the pooled fund study to investigate the practicality of proposed test method and equipment and develop a detailed specification. Percent compaction (PC) was used as a reference for the quality of compaction. It was observed that for the well-compacted material both the PC and $E_{field}/E_{target}$

criteria passed the specification limits, whereas the sites with inadequate compaction failed both criteria. This confirmed the applicability of LWD testing for modulus-based QA for field compaction.

Two draft specifications were developed for LWD testing in the field and target modulus determination in the lab. The specifications, written in AASHTO format, describe the steps required for LWD on mold and field LWD testing. This includes determination of the target modulus and the adjustment of the field surface modulus for the finite layer thickness effect for two-layer system when the two layers have significantly different moduli in the field. The specifications are written generally so that the agencies can adjust for their local material and equipment in practice.

Acceptance criteria and minimum required sampling frequency are suggested based on the data collected from the field sites and for the LWD devices used in this study.

To effectively implement the new LWD modulus-based QA approach, it is suggested that the agencies evaluate the specifications using their existing projects in conjunction with conventional density-based methods. The importance of having qualified and trained technicians for collecting and analyzing the LWD data cannot be over-emphasized.

The Maryland Department of Transportation State Highway Administration (MDOT SHA) collaborated with the research team on a follow up study to calibrate the LWD modulus-based QA specification for the Maryland's unbound geomaterials.

Similar to the pooled fund study, the follow-on MDOT SHA study employed Dynatest 3031 LWD testing performed concurrently with Troxler NDG measurements for a range of geomaterials commonly used for road base and embankment construction in the state of

Maryland. Field construction projects were identified by MDOT SHA personnel. A total of nine test sites were visited, with three additional graded aggregate base (GAB) samples obtained directly from the aggregate production plants.

Dynatest LWD testing on mold was used to establish the target modulus. Three to five molds were compacted for each soil type at around the optimum moisture content (OMC). LWD drops were performed on each mold at multiple drop heights.

As in the pooled fund study, PC and the field to $E_{field}/E_{target}$ were compared. Acceptable compaction quality is achieved when the PC of a layer is above the MDOT SHA's acceptable density limit and/or is deemed satisfactory by the field inspectors. Failing compaction quality is defined as failure to meet the MDOT SHA's MC or PC criteria and/or is judged as poor quality by field inspectors.

Compaction should be rejected when an unacceptable number of $E_{field}/E_{target}$ values fall below 1. The "unacceptable number" of failing $E_{field}/E_{target}$ values was determined using the percentage within specification limit (PWL) methodology (AASHTO R 9-05). A typical within-lot variability was also determined based on the coefficient of variation of all of the field modulus values measured in this study.

The results consistently showed that projects where conventional NDG test results (PC, MC) satisfied the MDOT SHA compaction QA specifications also had $E_{field}/E_{target}$ exceeding the lower limit of 1.

Target modulus values of six common Maryland GABs were measured and cataloged. Acceptance criteria of $E_{field}/E_{target}$ equal to 1 with a PWL of 80% and testing frequency of 10 random LWD measurements per quarter lane mile per lift were also recommended. An improved procedure to match field and lab testing pressure was also developed to eliminate the need for multiple drop heights during LWD testing on mold.

The long term outcomes and benefits from this study include: (1) re-emphasis of the shortcomings of current density based QA, density data collection, Proctor testing, and MDD determination; (2) identification of potential enhancements to the specifications for modulus based QA using LWDs to reduce the risks of accepting lower quality compaction; (3) implementation of variability analysis procedures for assessing compaction variability and incorporating this into the modulus-based specifications; and (4) emphasis of the need for better remediation strategies for rejection of lower quality road base and subgrade construction. It is also recommended that MDOT SHA engineers further assess the validity of the findings from this study by continuing to collect additional LWD and NDG data concurrently over the short to intermediate term.

# 9. Appendices

**Appendix A- Draft Specifications is AASHTO format**

**Standard Method of Test for**

# Laboratory Determination of Target Modulus Using Light-Weight Deflectometer (LWD) Drops on Compacted Proctor Mold

**AASHTO Designation: TP 123-01 (2017)**

## 1. SCOPE

1.1. This test method describes the procedure to determine the target modulus (or deflection) required for compaction quality control of geomaterials using Light Weight Deflectometer (LWD) drops on a compacted Proctor mold in the laboratory.

1.2. The same LWD type in terms of brand name, buffer stiffness, and deflection measurement location (on top of the plate or on top of the soil layer) used for the laboratory target modulus testing must be used during the field testing. This is to eliminate differences between measurements from different devices.

1.3. This procedure shall be performed in the laboratory on representative soil samples before the field compaction operations.

1.4. Gradation, moisture content inconsistency, and surface texture on the mold can affect the material moduli results.

1.5. The target surface modulus values can be compared to the field measured modulus in accordance with the TP 456-01 specification for compaction quality control/quality assurance purposes.

## 2. REFERENCED DOCUMENTS

2.1. *AASHTO Standards:*

- T 180, Moisture-Density Relations of Soils Using a 4.54-kg (10-lb) Rammer and a 457-mm (18-in.) Drop
- T 265, Laboratory Determination of Moisture Content of Soils
- T 248, Method of Test for Reducing Samples of Aggregate to Testing Size
- TP 456-01, Compaction Quality Control Using Light Weight Deflectometer

2.2. *ASTM Standards:*
- E 2583-07, Measuring Deflections with a Light Weight Deflectometer (LWD)
- E 2835-11, Measuring Deflections using a Portable Impulse Plate Load Test Device
- D 3665-12, Standard Practice for Random Sampling of Construction Materials

## 3. APPARATUS

3.1. *Mold*— Solid-wall, metal cylinders with dimensions and specification conforming to Section 3.1 of T 180. Only 152.4-mm (6-in.) diameter molds conforming to Section 3.1.2 of T 180 shall be used.

3.2. *Rammer*—A metal rammer conforming to Section 3.2 of T 180 for modified compaction energy.

3.3. *LWD*—

3.3.1 The LWD testing apparatus should conform to the general requirements of Section 5 of either ASTM E 2583 for LWDs with load cells or ASTM E 2835 for LWDs without load cells.

3.3.2 The signal conditioning and recording of the LWD testing apparatus should conform to either Sections 8 of ASTM E 2583 for LWDs with load cells or Section 6 of ASTM E 2835 for LWDs without load cells.

3.3.3 The LWD testing apparatus should be regularly calibrated and verified according to the requirements of Sections 7 of ASTM E 2583 for LWDs with load cells or Sections 7 and 8 of ASTM E 2835 for LWDs without load cells.

3.3.4 The precision and bias of the LWD testing apparatus shall conform to Sections 10.1-10.2 of ASTM E 2583 for LWDs with load cells or Sections 14.1-14.2 of ASTM E 2835 for LWDs without load cells.

3.4. *Miscellaneous Equipment*— Balances and scales, drying oven, straightedge, sieves, mixing tools, and containers conforming to the requirements of Sections 3.4 through 3.9 in T 180. A sample splitter or a similar tool conforming to the requirements of T 248.

## 4. PROCEDURE

4.1. This test is to be conducted as an add-on to the Proctor method of moisture-density relations of soils. Refer to T 180, method B or D for the compaction of the specimen with three to five different moisture contents. Below is a highlight of the steps and cautions that should be taken:

4.1.1 Take a sample of approximately 40 kg (~90 lb) required for compaction of the Proctor molds from the construction material according to ASTM D 3665.

4.1.2. Separate an appropriate quantity of about 7 kg (~15 lb) or more from the representative soil for the compaction of one mold according to T 248.
**Note 1**—Exclude oversize particle if the total retaining is less than 10% on the largest sieve size.

4.1.3. Use modified compaction energy according to methods B or D of T 180 to compact the specimen. Moisture content of the specimen can be selected roughly four percentage points below the material optimum moisture content based on experience, then added until the compaction curve is achieved (optional).
**Note 2**—Spread a uniform thickness including particles from all gradations in each layer.
**Note 3**—Avoid compacting and testing on a too damp soil where permanent deformation is observed after dropping the weight or excessive water is drained from the mold during the testing.

4.2. Rest the mold on a stable solid foundation or concrete floor. Carefully place the LWD with a 150-mm (5.905-in.) diameter loading plate on top of the mold and rotate approximately 45° back and forth to seat the plate. Any lateral movement of the plate with successive drops should be minimized.
**Note 4**—The diameter of the LWD plate is almost equal to mold diameter, so the plate should clear the rim of the mold (Figure 1, Appendix).
**Note 5**—A collar can be attached after trimming the compacted surface to help keep the LWD loading plate in place.

4.3. Hold the LWD rod vertical and conduct six drops at each drop height; Three seating drops followed by three measurement drops by raising the falling weight to each reduced drop height, then allowing the weight to fall freely without lateral movements. Refer to ASTM E 2583, ASTM E 2853*,* and the LWD device manuals from the manufacturer for further instruction.
**Note 6**—Drops from reduced heights are used to monitor the stress dependency of material and permit interpolation/ extrapolation to the field plate pressure. Table 1 in the Appendix recommends drop heights for Zorn, Dynatest, and Olson LWDs with standard 10 kg (22 lb) drop weights. In order to avoid testing at Multiple drop heights, the LWD pressure on mold maybe matched to the LWD pressure when testing in the field.
**Note 7**— The generated force by the drop should deliver a half-sine or haversine shaped load with pulse duration of between 20 and 40 msecs for the devices with

load cells (Section 5.3, ASTM E 2583) and between 10 and 30 msecs for devices without load cells (Section 5.4, ASTM E 2835). The load pulse duration depends on the soil modulus and can be adjusted by altering the LWD buffer stiffness, plate size, and drop mass weight.

4.4. Record the deflections and applied loads from each drop height and/or export these from the data storage system.
**Note 8**—In instances where the soil material is fragile in character and where the grain size distribution will be altered significantly by repeated compaction, a separate and new soil sample shall be used in each compaction test.
**Note 9**—Calculate and observe the coefficient of variation for the three measurement drops. Repeat the testing if the coefficient of variation is more than ten percent.

4.5. Remove the material from the mold, take representative samples immediately, and determine the moisture content in accordance with T 265 and record the results.
**Note 10**—Taking moisture samples from the mixing container is preferred in case water is drained from the bottom of the mold during the testing.

## 5. CALCULATION

5.1. Plot the moisture-density relationship and determine the optimum moisture content and maximum density following the procedures in Sections 12 and 13 of T 99 or T 180. Determine the acceptable moisture content ($MC_{field}$) range according to the agency requirements.

5.2. The modulus of the soil in the mold is derived from the theory of elasticity for a cylinder of elastic material with constrained lateral movement:

$$E = \left(1 - \frac{2v^2}{1-v}\right)\frac{4H}{\pi D^2}k \tag{1}$$

where:

$v$ = Poisson's ratio (refer to Table 2 for the suggested values),
$H$ = height of the mold,
$D$ = the diameter of the plate or mold,
$k$ = soil stiffness $=F/\delta$ as measured by the LWD device,
$F$ = average maximum applied load by the LWD during the three measurement drops, and
$\delta$ = average maximum deflection measured by the LWD during the three measurement drops.

5.3. Each drop height on the mold corresponds to an applied pressure ($P_{mold}$).

$$P_{mold} = \frac{F}{\pi\left(D/2\right)^2} \quad \textbf{\textit{(14)}}$$

**Note 11**— It is optional to normalize the applied pressure to the atmospheric pressure (*Pa*=101.325 kPa or 14.69 psi) for the analysis (*P/Pa*).
**Note 12**—For LWD devices that do not have a load cell (ASTM E 2835), the magnitude of the peak load for the lower drop heights is estimated as proportional to the square root of the drop height. Alternatively, the load for LWD devices that do not have a load cell can be calibrated for reduced drop heights.

5.4. A two-variable quadratic regression analysis should be performed to find the regression coefficients for LWD modulus measured on the mold as a function of the moisture content ($MC_{mold}$) and plate pressure.

$$E = a_0 + a_1 \times MC_{mold} + a_2 \times MC_{mold}^{\;2} + a_3 \times P_{mold} + a_4 \times P_{mold}^{\;2} \quad \textbf{\textit{(3)}}$$

where:
$a_0, a_1, a_2, a_3, a_4$ = regression coefficients.

5.5. The range of material target moduli values ($E_{target}$) shall be obtained by inputting the acceptable moisture content range from Section 5.1 and the field plate pressure into the regression equation.

$$E_{taregt} = a_0 + a_1 \times MC_{field} + a_2 \times MC_{field}^{\;2} + a_3 \times P_{field} + a_4 \times P_{field}^{\;2} \quad \textbf{\textit{(4)}}$$

**Note 13**—Field plate pressure ($P_{field}$) varies depending on the plate size and drop weight and can be determined as follows:

$$P_{field} = \frac{F_{field}}{\pi\left(\frac{D_{field}}{2}\right)} \quad \textbf{\textit{(5)}}$$

where:
$F_{field}$ = applied load from the LWD in the field, and
$D_{field}$ = the diameter of the LWD plate in the field.

**Note 14**—When the LWD pressure on mold is matching the field pressure, Section 5.4 and 5.5 can be skipped and LWD target is determined solely based on acceptable MC range.

5.6. The target modulus can be compared to the measured field modulus ($E_{field}$) to assess the compaction quality following TP 456-01 Section 5.

## 6. REPORT

6.1. The test report shall include the following:

- Acceptable moisture content range in percent to the nearest whole number.

- Maximum laboratory dry density value in pounds per cubic feet to the nearest whole number.
- The LWD device type used in laboratory testing on Proctor mold, the drop weight and plate diameter.
- LWD device to be used in the field, drop weight and plate diameter.
- Material target modulus range for 200-mm (7.87-in.) and/or 300-mm (11.81-in.) LWD plate sizes.
- Any corrections made in the reported values and the reason for the corrections (e.g. oversized particles, excessive water drainage unstable LWD plate, and/or poor contact with the compacted soil in the mold).

## 7. APPENDIX

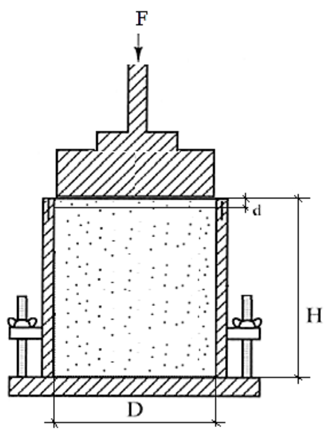



**Figure 1**— Schematic of LWD Testing on Proctor mold

**Table 1—** Suggested LWD Drop Heights on Proctor Mold for 10-kg Drop Weight

| LWD type | Drop Heights (in.) | | | | |
|---|---|---|---|---|---|
| Zorn | 2 | 3 | 4 | 5 | 12.5 |
| Dynatest | 3 | 4 | 5 | 8 | - |
| Olson | 2 | 3 | 4 | 5 | 8.5 |

**Table 2**—Typical Values of Poisson's Ratio (from MEPDG)

| Material | Range of values | Typical value |
|---|---|---|
| Untreated Granular Materials | 0.30 - 0.40 | 0.35 |
| Cement-Treated Granular Materials | 0.10 - 0.20 | 0.15 |
| Cement-Treated Fine-Grained Soils | 0.15 - 0.35 | 0.25 |
| Lime-Stabilized Materials | 0.10 - 0.25 | 0.2 |
| Loose Sand or Silty Sand | 0.20 - 0.40 | 0.3 |
| Dense Sand | 0.30 - 0.45 | 0.35 |
| Saturated Soft Clays | 0.40 - 0.50 | 0.45 |
| Silt | 0.3 – 0.35 | 0.32 |

| | | |
|---|---|---|
| Clay (Unsaturated) | 0.1 – 0.3 | 0.2 |
| Sandy Clay | 0.2 – 0.3 | 0.25 |
| Coarse-grained Sand | 0.15 | 0.15 |
| Fine-grained Sand | 0.25 | 0.25 |

Standard Method of Test for

# Compaction Quality Control Using Light Weight Deflectometer (LWD)

## AASHTO Designation: TP 456-01 (2017)

## 1. SCOPE

1.1. This test method describes the procedure to assure the compaction quality of a road base or subgrade by comparing the field surface moduli to the laboratory determined target moduli using a Light Weight Deflectometer (LWD).

1.2. The same LWD type in terms of brand name, buffer stiffness, and deflection measurement location (on top of the plate or on top of the soil layer) used for the laboratory target modulus testing must be used during the field testing. This is to eliminate differences between measurements from different devices.

1.3. This procedure shall be performed within two hours after compaction to eliminate the effect of surface drying on the modulus values. This method does not count for post compaction wetting/drying and environmental effects.

1.4. An appropriate in situ method of soil moisture content measurement shall be used to rapidly determine the moisture content at the time of compaction and testing.

1.5. The target modulus should be corrected for a base or subbase layer of finite thickness compacted over subgrade.

## 2. REFERENCED DOCUMENTS

2.1. *AASHTO Standards*:
- T 265, Laboratory Determination of Moisture Content of Soils
- R 9-05, Acceptance Sampling Plans for Highway Construction
- AASHTO Guide for the Design of Pavement Structures (1993)
- TP 123-01, Laboratory Determination of Target Modulus Using Light-Weight Deflectometer Drops on Compacted Proctor Mold

2.2. *ASTM Standards*:
- E 2583-07, Measuring Deflections with a Light Weight Deflectometer (LWD)
- E 2835-11, Measuring Deflections using a Portable Impulse Plate Load Test Device
- D 3665-12, Standard Practice for Random Sampling of Construction Materials

- D 4643-00, Determination of Water (Moisture) Content of Soil by the Microwave Oven Heating
- D 4944-11, Field Determination of Water (Moisture) Content of Soil by the Calcium Carbide Gas Pressure Tester
- D 4959-16, Determination of Water Content of Soil by Direct Heating

## 3. APPARATUS

3.1. *LWD*—

3.1.1 The LWD testing apparatus should conform to the general requirements of Section 5 of either ASTM E 2583 for LWDs with load cells or ASTM E 2835 for LWDs without load cells.

3.1.2 The signal conditioning and recording of the LWD testing apparatus should conform to either Sections 8 of ASTM E 2583 for LWDs with load cells or Section 6 of ASTM E 2835 for LWDs without load cells.

3.1.3 The LWD testing apparatus should be regularly calibrated and verified according to the requirements of Sections 7 of ASTM E 2583 for LWDs with load cells or Sections 7 and 8 of ASTM E 2835 for LWDs without load cells.

3.1.4 The precision and bias of the LWD testing apparatus shall conform to Sections 10.1-10.2 of ASTM E 2583 for LWDs with load cells or Sections 14.1-14.2 of ASTM E 2835 for LWDs without load cells.

3.2. *Moisture Content Testing*—An appropriate in situ method of soil moisture (water) content measurement shall be used to rapidly determine the moisture content at the time of compaction and testing. Example equipment for accomplishing this include the Ohaus Moisture Analyzer, Microwave Oven (ASTM D 4643), Field Stove (ASTM D 4959), Speedy Moisture Tester (ASTM D 4944), etc. and a portable power generator if deemed necessary.

3.3. *Miscellaneous Equipment*—
- A small square shovel or similar tool to level the testing surface.
- A soil sampler and sealed containers/bags to collect the moisture content samples.
- Marking spray to designate the LWD testing locations.
- Tape measure or measuring wheel.

## 4. PROCEDURE

4.1. Determine the LWD model, acceptable moisture content range and corresponding $E_{target}$, and assumed Poisson's ratio following the TP 123-01 specification in advance of the compaction operation. Input the Poisson's ratio and the appropriate

shape factor from Table 1 into the LWD device.
**Note 1**—Different LWDs report different moduli values. The same LWD type in terms of manufacturer, model, and buffer stiffness used for the laboratory target modulus testing must be used for the field testing.

4.2. Control of moisture content is a critical factor in attaining proper compaction of geomaterials.

4.2.1. Take at least three random moisture samples per sublot per ASTM D 3665 or similar. One sample shall be taken during placing/spreading of each lift and two samples shall be taken immediately after compaction.

4.2.2. Use the moisture content testing equipment appropriate for field use (Section 3.2) to measure the moisture content of each sample.

4.2.3. The average moisture content shall comply the acceptance requirement in Section 7.1.

4.2. Identify random LWD testing locations per ASTM D 3665 or similar. The minimum testing frequency is specified in Section 6.2. Mark and label the LWD testing locations.
**Note 2**—LWD testing shall be performed within two hours of compaction to avoid moisture loss. The average moisture content of the two samples at the time of testing may not deviate more than 2 percentage points from the sample obtained at the time of the layer placement.

4.3. Record the LWD testing locations and any noteworthy remarks.

4.4. Carefully clear and level the area underneath the LWD plate without any disturbance to the compacted surface. Remove loose oversized rocks. In case of open graded base material, a thin layer of sand can be used to fill in the gaps to provide full contact with the plate.

4.5. Position the load plate and rotate left and right approximately 45 degrees to achieve intimate contact between the plate and soil surface.

4.6. Perform 6 drops following the manufacturer’s instructions and in general accordance with ASTM E 2583 for LWDs with load cells and ASTM E 2835 for LWDs without load cells. The first three drops are for the seating and the second three drops are for modulus measurement. Record the reported device data storage file names and moduli values (optional).
**Note 3**—When testing a base layer of finite thickness, it is necessary to perform LWD testing on the surface of the underlying soil before the base material placement. These tests should be performed at the same locations (determined by Section 4.2) on the same day that the base is placed. Then perform the LWD

testing on top of the compacted base layer and correct the target modulus as described in Section 5.3.

**Note 4**—During LWD testing, pay attention to the deflections/modulus for each drop. Repeat the testing at an adjacent location in case an outlier deflection/modulus data captured for a drop.

## 5. CALCULATION

5.1. The field modulus is calculated using the half space Boussinesq equation assuming the test media to be a linear elastic, isotropic, and homogeneous semi-infinite continuum:

$$E_{field} = \frac{2k(1-v^2)}{Ad} \quad (1)$$

$E_{field}$ = field modulus,
$k$ = average soil stiffness $=F/\delta$ as measured by LWD device,
$F$ = maximum load applied by the LWD device,
$\delta$ = maximum deflection measured by the LWD device,
$A$ = stress distribution factor ($\pi$ for mixed soils, $3\pi/4$ for granular material, and 4 for cohesive material.
$v$ = Poisson's ratio obtained from Section 4.1, and
$d$ = LWD plate radius.

5.2. *Target Modulus for Subgrade and Embankment*—The subgrade layer is assumed to be infinite in extent in the horizontal and downward vertical directions. So, the target modulus is equivalent to the material target modulus at a given moisture content as obtained from TP 123-01.

5.3. *Target Surface Modulus for Base Courses*—According to *AASHTO Guide for the Design of Pavement Structures (AGDPS)*, the total surface deflection directly under the circular load (LWD plate) is the summation of deformation occurring in the top and bottom layer. When evaluating a base layer of finite thickness, the target modulus obtained from Section 4.1 should be corrected using Equation 2 or Figure 1 in the Appendix. The corrected $E_{target}$ is then used to compare to $E_{field}$.

$$E_{target-corr} = 1 \Bigg/ \left\{ \frac{1}{E_2\left[\sqrt{1+\left(\frac{h}{d}\sqrt[3]{\frac{E_1}{E_2}}\right)^2}\right]} + \frac{\left[1-\frac{1}{\sqrt{1+\left(\frac{h}{d}\right)^2}}\right]}{E_1} \right\} \quad \textbf{(2)}$$

$E_{target-corr}$ = corrected target modulus for the base material,
$E_2$ = modulus of the foundation (subgrade, or subbase plus subgrade) measured by the LWD before base placement according to Section 4.6,
$E_1$ = target modulus for the base material from the TP 123-01 ($E_{target}$ from Section 4.1),
$h$ = base layer thickness, and
$d$ = LWD plate radius used during field testing.

5.4. Calculate the ratio $E_{field}/E_{target}$ for subgrade and embankment materials or $E_{field}/E_{target-corr}$ for finite thickness base layers.

## 6. SAMPLING FREQUENCY

6.1. In order to assure that LWD testing is performed over the entire lot and not concentrated in one area, stratified random sampling using random locations within sublots is recommended according to ASTM D 3665.

6.2. The minimum frequency of LWD test shall be as outlined herein. Additional testing shall be performed if deemed necessary by the Engineer.

- For subgrade, base, and subbase compaction: Divide each lane mile into 4 subsections per lift and perform a minimum of 10 LWD tests per subsection at random locations.
- For road embankment material that is 1 ft or more below the top of subgrade: Divide each lane mile into 4 subsections per lift and perform a minimum of 5 LWD tests per sublot at random locations.

## 7. ACCEPTANCE

7.1. The average moisture content of the samples collected immediately after compaction shall fall within the acceptable moisture content range as determined by the TP 456-01 specification and agency policy.

7.2. The field to target ratios calculated per Section 5.4 shall be evaluated for acceptance using the percentage of material within specification limits method (PWL) following R 9-05 specification. The preliminary recommendations for lower specification limit shall be 1 with a PWL of 80%.

7.3. A spatial COV of about 20% shall be maintained to ensure uniform compaction within the lot.

7.4. The lot shall be rejected once a "large" percentage is outside the specification limit according to R 9 Section 8.12.7. Local agencies may want to perform additional implementation studies to refine the lower specification limit and/or the acceptable PWL. Typically, the lot may be rejected if PWL is less than 50%.

7.5. Appropriate remedial procedures shall be adopted for the materials that do not meet the acceptance criteria. These materials shall be re-tested for acceptance after corrections.

## 8. REPORT

8.1. The test report shall include the following:

- Project location and weather description.
- Material type, lift number, layer thickness, and construction timeline.
- Moisture content measurement device, number of samples and locations, percent moisture content.
- LWD model used during field testing, plate size, drop height, and drop weight.
- Recorded test area coordinates and numbered test locations.
- Target modulus correction for finite layered thickness and LWD plate radius.
- Test location identification and measured LWD moduli or device file name at each location.

## 9. SAFETY

9.1. Carefully follow the manufacturer's instructions on the LWD device assembly and operation. To prevent any damage to the device, make sure all the parts are firmly attached before dropping the load in the field.

9.2. Keep the back straight and lift the weight with leg muscles to avoid back strain.

9.3 Always secure the safety interlock when pausing the test or transporting the LWD to new locations.

9.4. Avoid placing the hands below the elevated drop weight.

# 10. APPENDIX

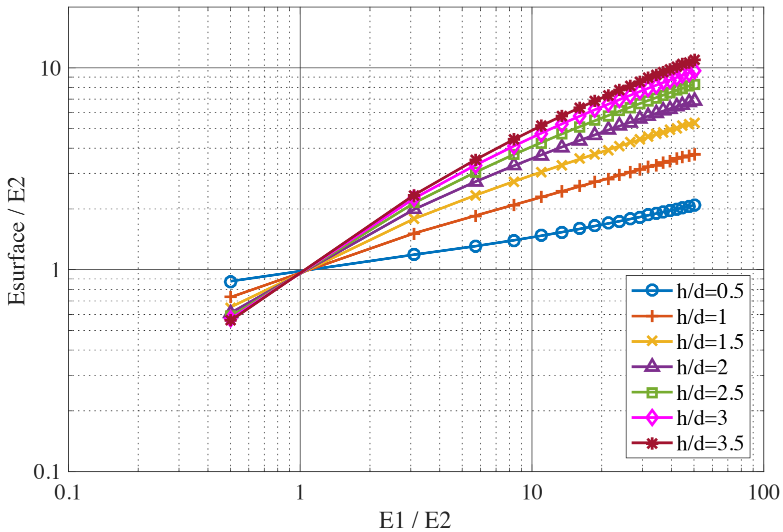



**Figure 1**— Surface Modulus Correction for Testing on Compacted Base Layer of Finite Thickness (h = base layer thickness, d = LWD plate radius used during field testing

## Appendix B- Field verification testing (from TPF(05)-285 pooled fund study)

### *Virginia*

**Project:** Tola road subgrade and base compaction

**Address:** 1603 Tola Road, Phoenix Virginia 23959, GPS: 37.074161, -78.754267

**Remarks:**

- Subgrade was compacted a week prior to the testing date. Subgrade surface was noticeably dry at the time of testing.
- Some compacted sections of dried stiff clay carried by the trucks or compaction rollers from the other part of the road existed on the test site.
- Due to thunderstorm, the construction was canceled and no LWD testing was performed on the base layer.


**Figure 99. Aerial view of the virgina Tola road evaluation site and test locations**

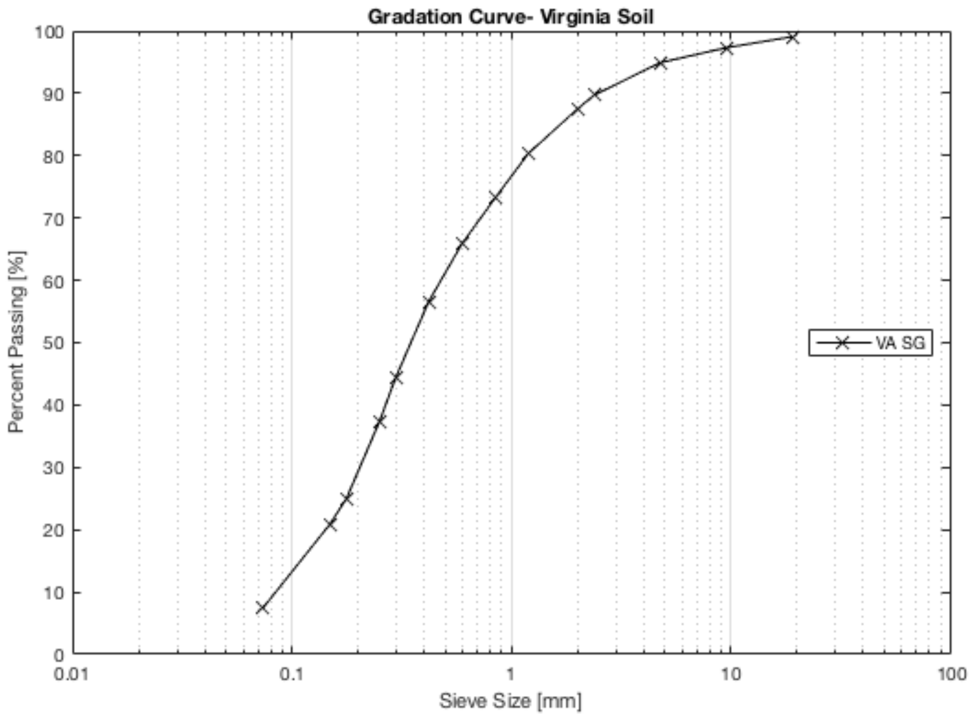



**Figure 100. Gradation Curve of Virginia site geomaterials**

*Maryland*

**Project:** MD 5 embankment construction and subgrade compaction on the embankment (Contract number PG494)

**Address:** MD 5, from Auth way to South of I-495/I-95

**Remarks:**

- A 2 feet deep embankment was compacted with a waste contaminated soil. The soil contained large pieces of recycled material such as glass, rubber and metal parts. Testing carried out every 1 hour on the 100 ft test section for 2 rounds.
- After a week, the subgrade material was placed over the dried embankment with a slope of about 3%.
- Testing carried out every 1 hour on the 100 ft test section for 3 rounds.

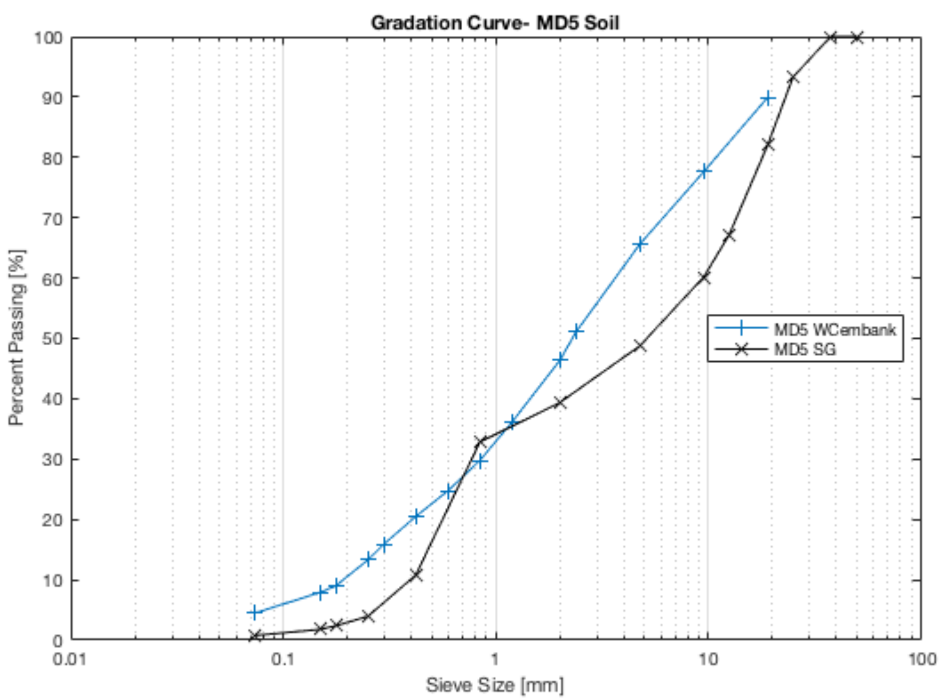



**Figure 101. Gradation Curve of MD5 site geomaterials**


**Figure 102. Aerial view of the MD5 field evaluation site**

**Project:** MD 337 lane widening

**Address:** 4701 Allentown road, Suitland, MD

**Remarks:**

- The local subgrade was a weak clay, so the lane was undercut for 3 ft. and replaced with GAB material. The initial 2 ft was compacted earlier.
- Testing was performed on top of a 6 inches GAB layer placed over the existing 2-ft layer.
- The 6-inch layer was compacted the day before testing at the end of the day. However, very little surface drying was observed on the top 0.5 inches.
- NDG was not available on site on the day of testing. Testing performed earlier on the 6-inch compacted layer reported PC of 98%.

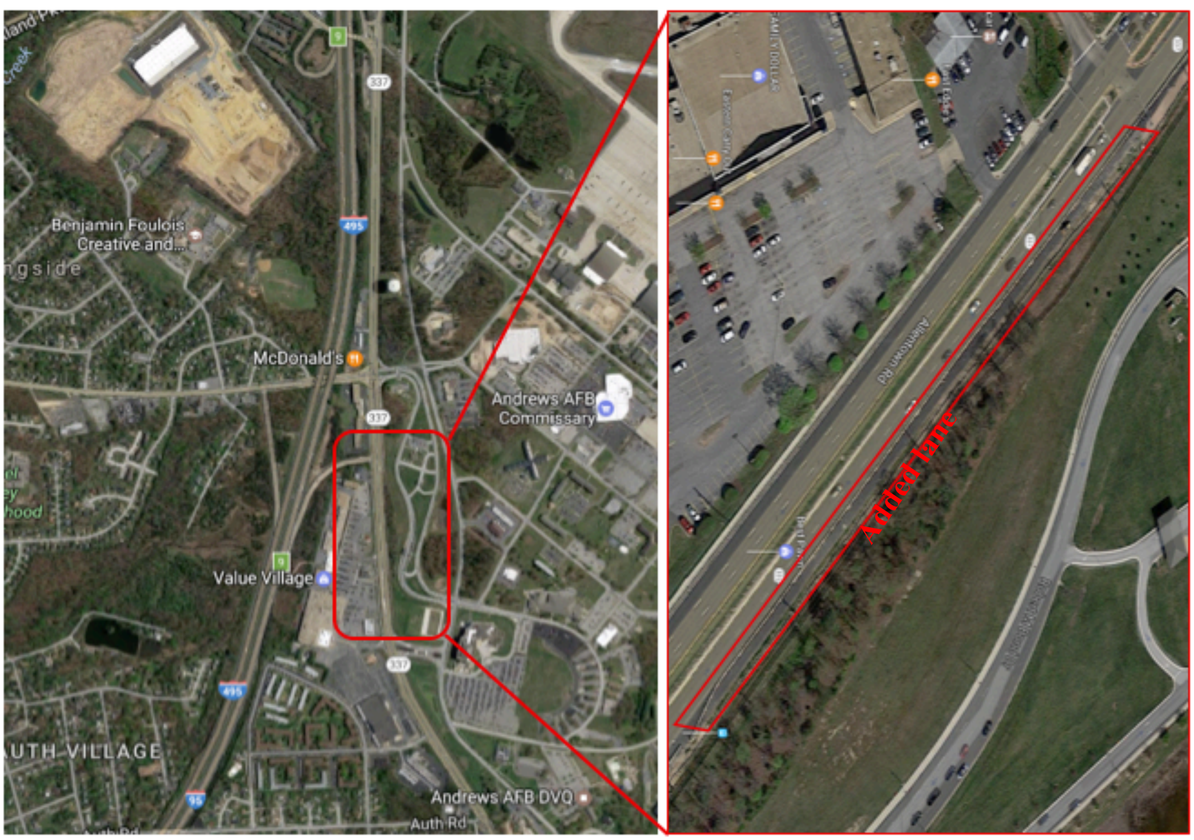


**Figure 103. Aerial view of the MD337 field evaluation site**

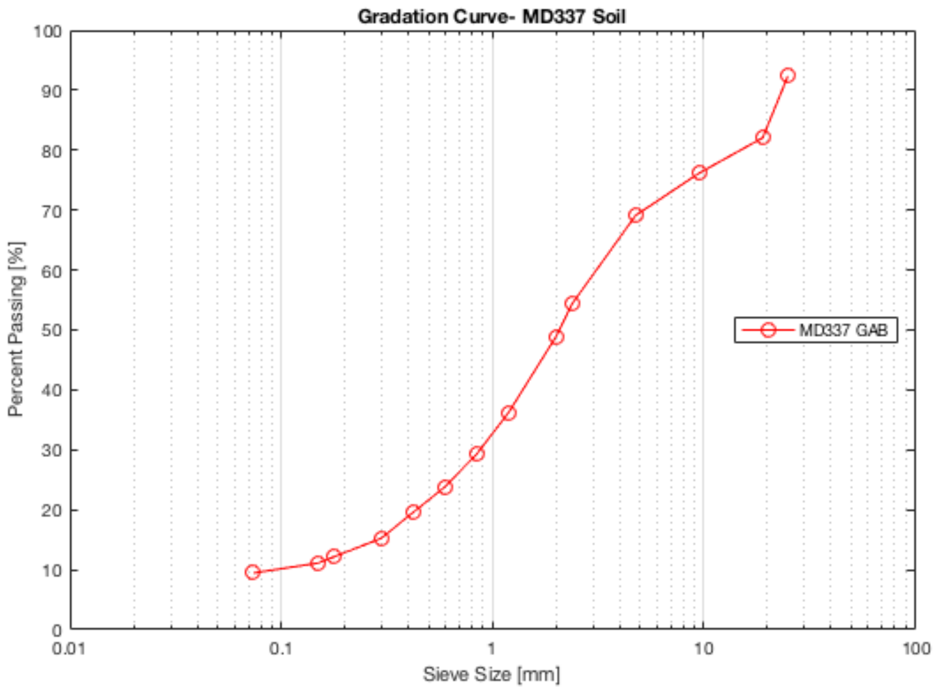



**Figure 104. Gradation Curve of MD337 site geomaterials**

**Project:** MD 404 dualization (Contract number AW8965270)

**Address:** 11419 Ridgely Rd, Ridgely, MD 21660

**Remarks:**

- A 5-ft embankment of local subgrade was compacted previously. Since the subgrade material was too wet at the time of placing the base, a 4-inch layer of uniform sand was compacted over the existing subgrade.
- Testing performed right after compaction on the sand layer.
- The GAB base layer was compacted in a layer of 6 to 8 inches.
- Testing performed right after GAB compaction.


**Figure 105. Aerial view of the MD404 field evaluation site**

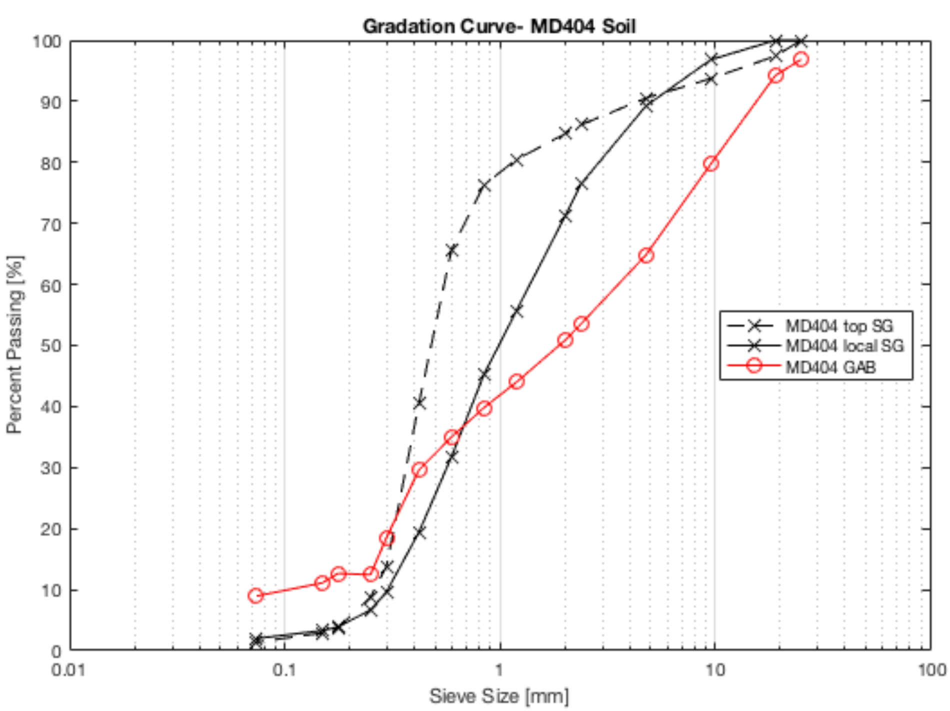



**Figure 106. Gradation Curve of MD404 site geomaterials**

*New York*

**Project:** Luther Forest Boulevard extension

**Address:** 3 Hemphill Pl Ballston Spa, NY 12020 (project office)

**Remarks:**

- The embankment constructed in layers of 8 inch to 1 ft thickness below the final grade.
- LWD and NDG testing performed on two lifts.
- The water content of the material was dryer than OMC at the time of compaction. Therefore, a truck was spraying water on top of the sand after placement. Spraying water was not possible on the test site as the LWD testing personnel were working.

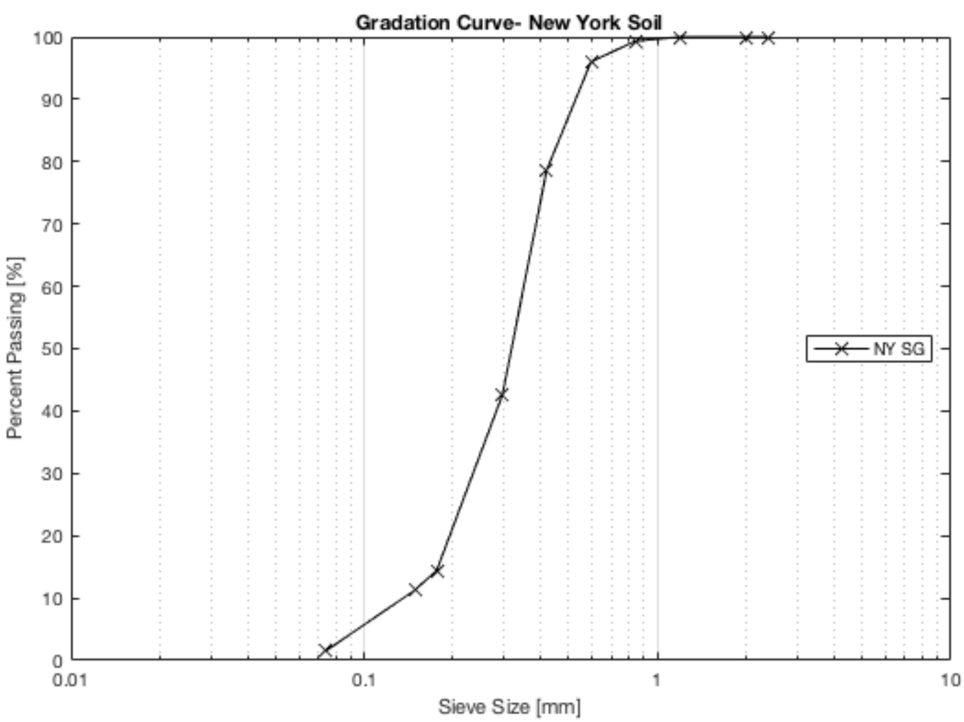



**Figure 107. Gradation Curve of New York site geomaterials**

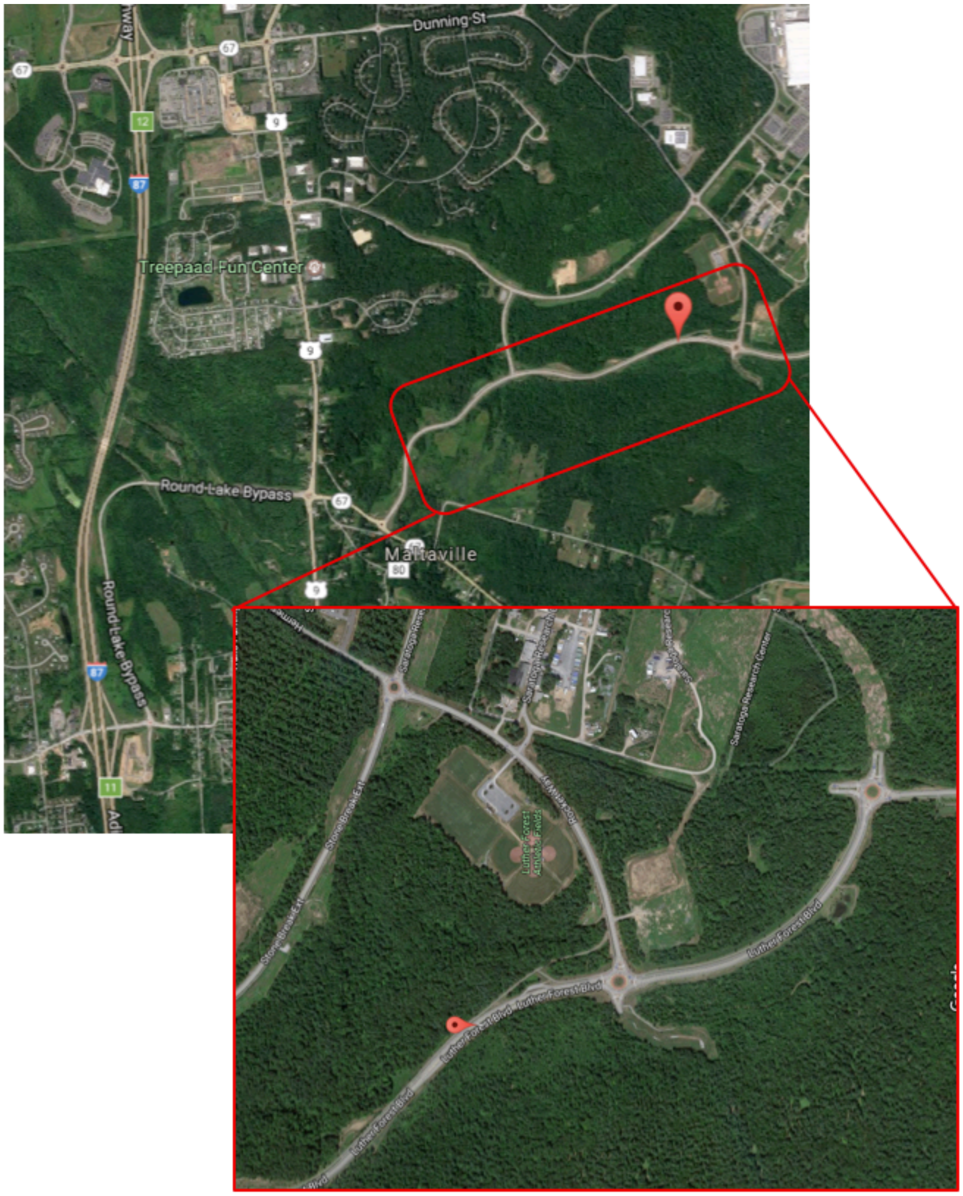



**Figure 108. Aerial view of the New York Luther Forest Boulevard evaluation site**

***Missouri***

**Project:** I-64 lane widening and road shoulder compaction

**Address:** 601 Salt Mill Rd, Chesterfield, MO 63017 (project office)

**Remarks:**

- The concrete shoulder on the I-64 lane was removed to add lane. The natural dirt (subgrade) below the shoulder was only compacted with 1 to 2 passes of roller compactor.
- A layer of about 4 inches of crushed lime stone (base) had been placed on top of the subgrade.
- Since the base layer was already placed, we were unable to perform LWD testing on the subgrade. Soil samples were collected from the subgrade for lab testing.
- LWD and NDG testing on the base layer performed right after compaction in two rounds of one hour interval.

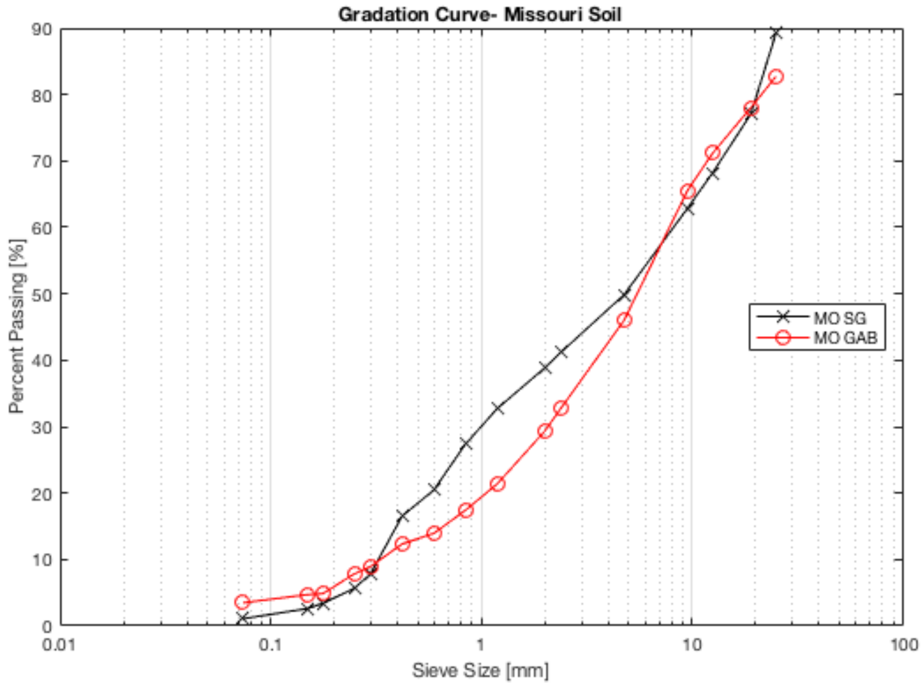



**Figure 109. Gradation Curve of Missouri site geomaterials**


**Figure 110. Aerial view of the Missouri I-64 evaluation site**

***Indiana***

**Project:** I-65 to Worthsville road and Graham road construction (R-35187-A)

**Address:** 1615 S Graham Road, Greenwood, IN 46143

**Remarks:**

- Cement stabilized subgrade was compacted 5 days before testing. The layer's thickness was 14 inches total.
- The subgrade was cured and very stiff to excavate for moisture samples at the time of testing. Therefore, water content samples were obtained from the depth of 3 to 6 inches from the trench on the side on the road. The water content was measured using the Ohaus moisture analyzer on the site.
- INDOT does not use NDG tests for routine compaction quality control anymore. INDOT used Zorn LWD testing and proof rolling with a fully loaded tri-axle truck to evaluate the compaction.
- Base material was compacted on top of the cured cement stabilized subgrade (3 inches thickness).
- Testing on the base performed right after compaction on almost the same locations as the subgrade testing.

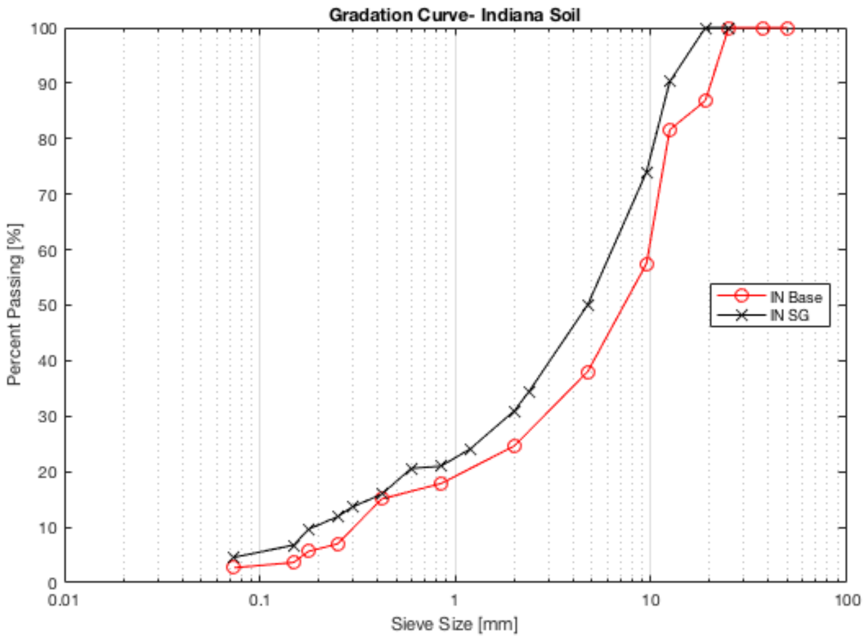



**Figure 111. Gradation Curve of Indiana site geomaterials**

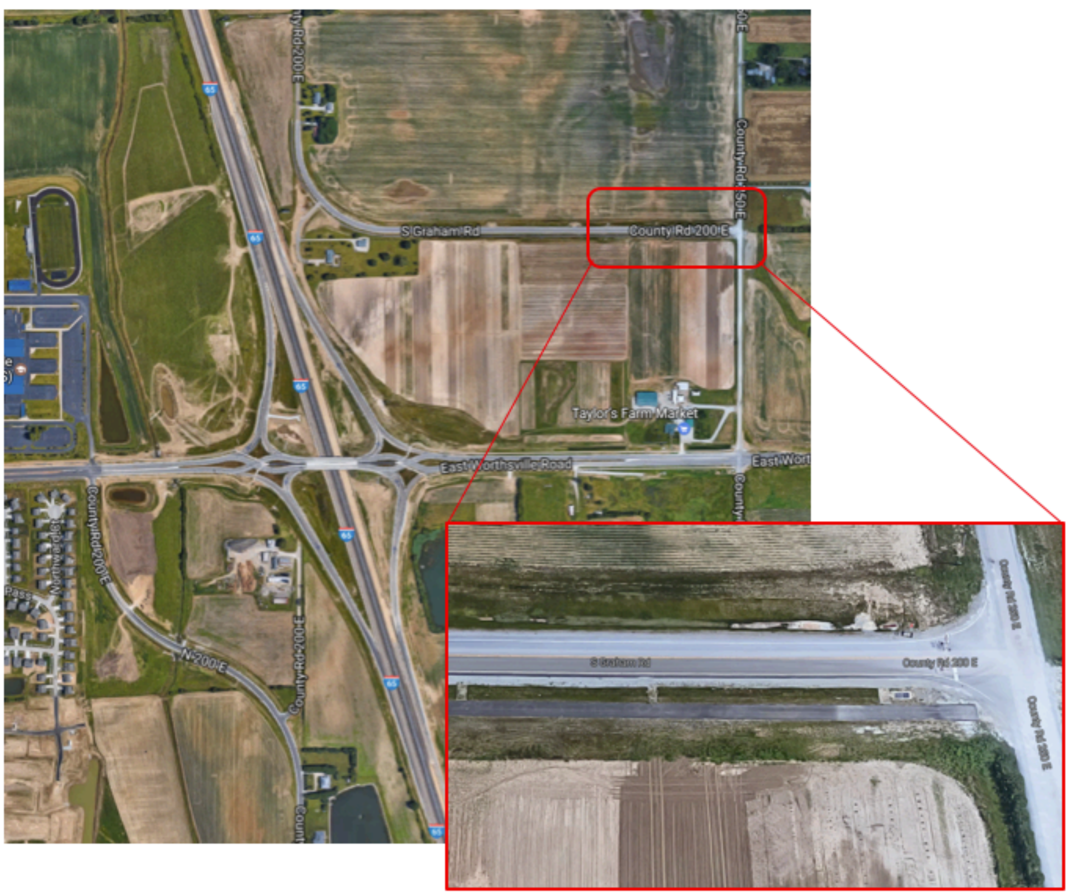



**Figure 112. Aerial view of the Indiana Graham road evaluation site**

***Florida***

**Project:** SR 23 construction, South Jacksonville, FL

From SR 21 (blanding Blvd.) to: duval county line

**Address:** Branan Field Rd, Orange Park, FL 32065

**Remarks:**

- Subgrade was compacted a week before LWD testing in the field. LWD and NDG testing on the subgrade performed right before base placement.
- Lime base material was compacted to a thickness of 6 to 8 inches. LWD and NDG testing on the base performed right after compaction in two rounds of one hour interval.

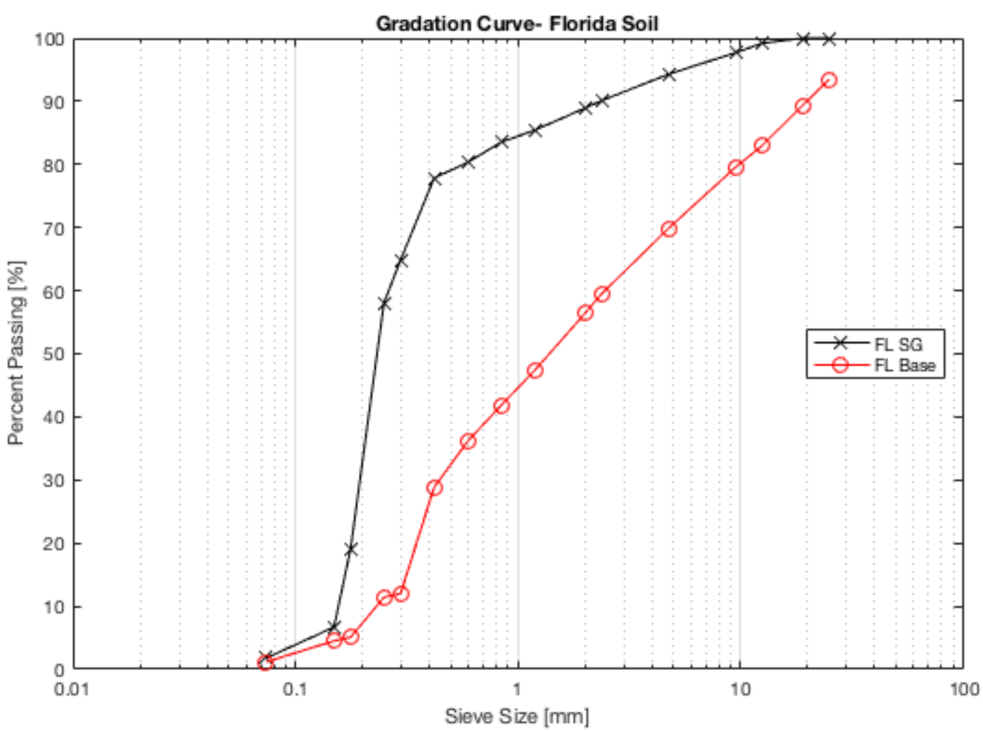



**Figure 113. Gradation Curve of Florida site geomaterials**

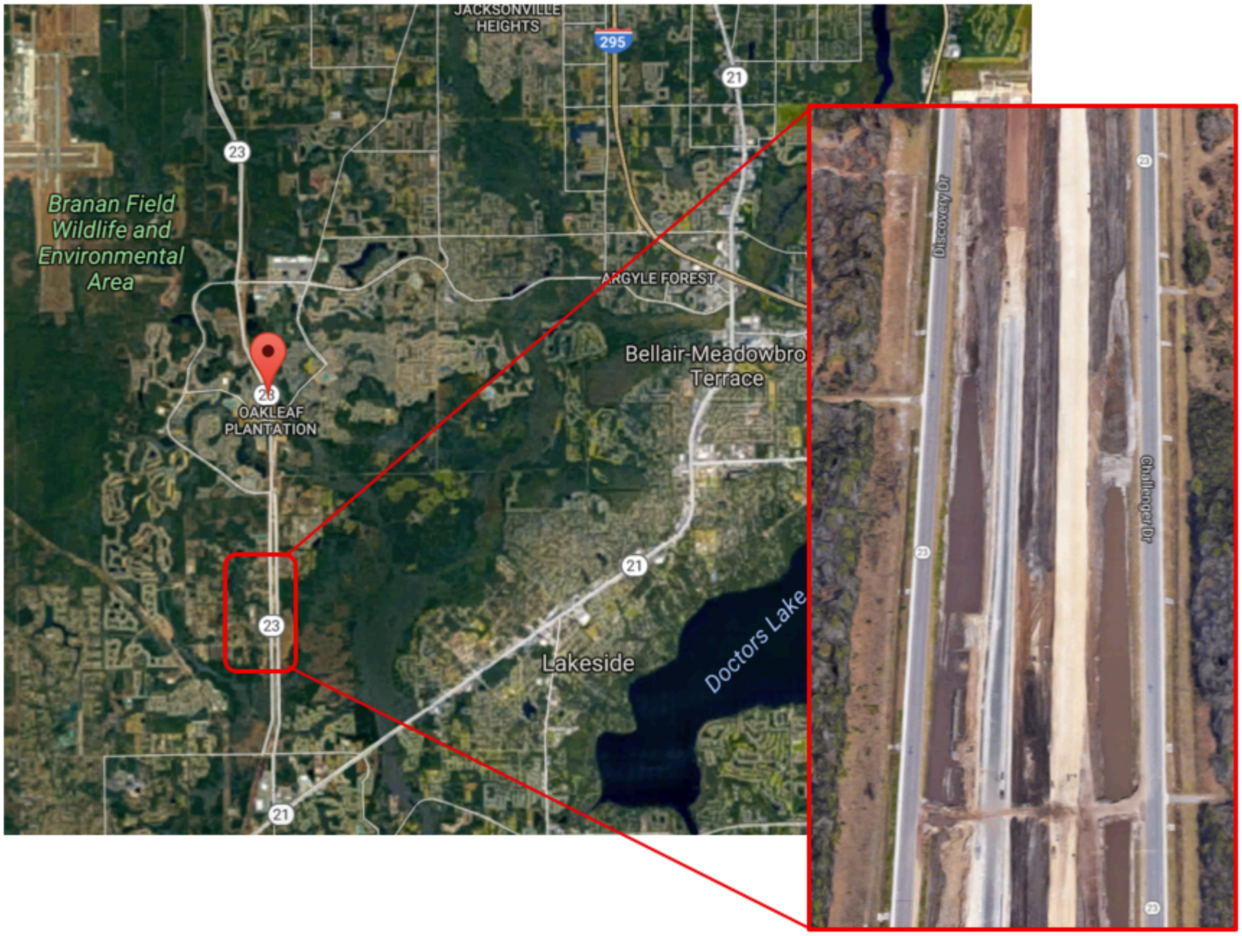



**Figure 114. Aerial view of the Florida SR23 field evaluation site**

# Appendix C- Summary of LWD field moduli, measured MC, and NDG results (from TPF05-285 pooled fund study)

**Table 31. Summary of field water content measured by NDG**

| Location and Soil Type | Round of Testing | Average MC [%] by NDG | Standard Deviation | %COV |
|---|---|---|---|---|
| Virginia, Phenix subgrade | 1st | 12.96 | 5.20 | 40.11 |
| MD 5 waste contaminated embankment | 1st | 9.94 | 2.60 | 26.19 |
| | 2nd | 9.46 | 2.18 | 23.02 |
| MD 5 subgrade | 1st | 4.32 | 0.33 | 7.57 |
| | 2nd | 3.88 | 0.35 | 9.00 |
| | 3rd | 4.22 | 0.78 | 18.38 |
| MD 404 subgrade | 1st | 6.01 | 0.78 | 13.04 |
| MD 404 GAB | 1st | 2.81 | 0.28 | 10.13 |
| New York, embankment (local subgrade) | Lift 1, 1st | 4.85 | 0.49 | 10.02 |
| | Lift 1, 2st | 4.72 | 0.58 | 12.26 |
| | Lift 2, 1st | 4.79 | 0.49 | 10.15 |
| | Lift 2, 2nd | 4.68 | 0.59 | 12.69 |
| Missouri, GAB | 1st | 4.53 | 0.90 | 19.78 |
| | 2nd | 4.31 | 0.69 | 16.07 |
| Florida, Subgrade | 1st | 8.11 | 1.01 | 12.42 |
| Florida, Base | 1st | 12.75 | 0.98 | 7.68 |
| | 2nd | 12.12 | 0.53 | 4.35 |

**Table 32. Summary of field water content obtained by oven drying method**

| Location and Soil Type | Round of Testing | Average MC [%] by Oven drying | Standard Deviation | %COV |
|---|---|---|---|---|
| Virginia, Phenix subgrade | 1st | 8.70 | 2.92 | 33.57 |
| MD 5 waste contaminated embankment | 1st | 11.30 | 3.42 | 30.28 |
| | 2nd | 10.38 | 2.39 | 23.05 |
| MD 5 subgrade | 1st | 4.34 | 0.35 | 7.98 |
| | 2nd | 3.37 | 0.40 | 11.76 |
| | 3rd | 2.56 | 0.89 | 34.61 |
| MD 337, deep GAB layer | 1st | 2.40 | 0.42 | 17.50 |
| New York, embankment (local subgrade) | Lift 1, 1st | 6.24 | 0.63 | 10.12 |
| | Lift 1, 2st | N/A | N/A | N/A |
| | Lift 2, 1st | 5.79 | 0.44 | 7.55 |
| | Lift 2, 2nd | 6.00 | 0.47 | 7.85 |
| Indiana, cement modified subgrade | 1st | N/A | N/A | N/A |
| Indiana, GAB | 1st | 6.44 | 0.32 | 4.98 |
| Missouri, GAB | 1st | 4.77 | 0.92 | 19.27 |
| | 2nd | 4.63 | 0.60 | 12.91 |
| Florida, Subgrade | 1st | 8.79 | 0.90 | 10.25 |

| | | | | |
|---|---|---|---|---|
| Florida, Base | 1st | 12.95 | 0.64 | 4.91 |
| | 2nd | 12.88 | 0.66 | 5.12 |

**Table 33. Summary of Percent Compaction values measured by NDG in the field**

| Location and Soil Type | Round of Testing | Average %PC | Standard Deviation | %COV |
|---|---|---|---|---|
| Virginia, Phenix subgrade | 1st | 96.8 | 4.525 | 4.673 |
| MD 5 waste contaminated embankment | 1st | 97.9 | 4.857 | 4.960 |
| | 2nd | 98.3 | 3.977 | 4.042 |
| MD 5 subgrade | 1st | 98.6 | 2.328 | 2.360 |
| | 2nd | 98.4 | 1.674 | 1.700 |
| | 3rd | 98.8 | 1.527 | 1.545 |
| MD 337, deep GAB layer | 1st | 98.0 | N/A | N/A |
| MD 404 subgrade | 1st | N/A | N/A | N/A |
| MD 404 GAB | 1st | 90.2 | 1.214 | 1.345 |
| New York, embankment (local subgrade) | Lift 1, 1st | 84.8 | 1.565 | 1.845 |
| | Lift 1, 2st | 85.4 | 2.531 | 2.963 |
| | Lift 2, 1st | 83.2 | 2.020 | 2.425 |
| | Lift 2, 2nd | 83.2 | 1.950 | 2.343 |
| Indiana, cement modified subgrade | 1st | N/A | N/A | N/A |
| Indiana, GAB | 1st | N/A | N/A | N/A |
| Missouri, GAB | 1st | 100.0 | 3.585 | 3.584 |
| | 2nd | 99.6 | 3.339 | 3.354 |
| Florida, Subgrade | 1st | 90.8 | 1.462 | 1.609 |
| Florida, Base | 1st | 102.7 | 1.617 | 1.574 |
| | 2nd | 102.4 | 1.327 | 1.295 |

**Table 34. Summary of Olson LWD moduli on the field sites**

| Location and Soil Type | Round of Testing | Average $E_{field}$ [MPa] Olson LWD | Standard Deviation | %COV |
|---|---|---|---|---|
| Virginia, Phenix subgrade | 1st | 19.484 | 13.920 | 71.446 |
| MD 5 subgrade | 1st | 82.100 | 36.179 | 44.067 |
| | 2nd | 77.571 | 27.815 | 35.858 |
| | 3rd | 72.237 | 22.395 | 31.003 |
| MD 337, deep GAB layer | 1st | 68.752 | 7.705 | 11.207 |
| MD 404 subgrade | 1st | 36.704 | 6.408 | 17.458 |
| MD 404 GAB | 1st | 35.997 | 5.229 | 14.526 |
| New York, embankment (local subgrade) | Lift 1, 1st | 22.495 | 4.068 | 18.084 |
| | Lift 2, 1st | 19.299 | 2.987 | 15.476 |
| | Lift 2, 2st | 19.366 | 3.517 | 18.159 |
| Indiana, cement modified subgrade | 1st | 101.530 | 45.238 | 44.556 |
| Indiana, GAB | 1st | 82.826 | 27.852 | 33.627 |
| Missouri, GAB | 1st | 46.834 | 13.826 | 29.523 |
| | 2nd | 55.494 | 16.285 | 29.345 |

**Table 35. Summary of Zorn LWD moduli on the field sites**

| Location and Soil Type | Round of Testing | Average $E_{field}$ [MPa] Zorn LWD | Standard Deviation | %COV |
|---|---|---|---|---|
| Virginia, Phenix subgrade | 1st | 27.786 | 22.281 | 80.187 |
| MD 5 waste contaminated embankment | 1st | 10.401 | 4.019 | 38.641 |
| | 2nd | 11.983 | 5.542 | 46.248 |
| MD 5 subgrade | 1st | 65.954 | 25.801 | 39.119 |
| | 2nd | 62.536 | 24.884 | 39.792 |
| | 3rd | 69.263 | 23.889 | 34.491 |
| MD 337, deep GAB layer | 1st | 64.713 | 8.059 | 12.454 |
| MD 404 subgrade | 1st | 33.404 | 8.752 | 26.199 |
| MD 404 GAB | 1st | 35.122 | 5.519 | 15.714 |
| New York, embankment (local subgrade) | Lift 1, 1st | 19.861 | 2.797 | 14.083 |
| | Lift 1, 2st | 22.338 | 2.752 | 12.321 |
| | Lift 2, 1st | 19.096 | 3.595 | 18.828 |
| | Lift 2, 2nd | 19.499 | 3.776 | 19.364 |
| Indiana, cement modified subgrade | 1st | 82.240 | 41.411 | 50.354 |
| Indiana, GAB | 1st | 71.105 | 27.580 | 38.787 |
| Missouri, GAB | 1st | 39.209 | 11.040 | 28.156 |
| | 2nd | 46.455 | 12.508 | 26.925 |
| Florida, Subgrade | 1st | 71.521 | 7.265 | 10.157 |
| Florida, Base | 1st | 66.411 | 10.155 | 15.292 |
| | 2nd | 73.261 | 9.858 | 13.456 |

**Table 36. Summary of Dynatest LWD moduli on the field sites**

| Location and Soil Type | Round of Testing | Average Efield, Dynatest LWD | Standard Deviation | %COV |
|---|---|---|---|---|
| Virginia, Phenix subgrade | 1st | 94.686 | 78.797 | 83.219 |
| MD 5 waste contaminated embankment | 1st | 14.881 | 7.868 | 52.872 |
| | 2nd | 22.009 | 12.266 | 55.732 |
| MD 5 subgrade | 1st | 157.309 | 126.146 | 80.190 |
| | 2nd | 173.242 | 113.957 | 65.779 |
| | 3rd | 197.286 | 179.677 | 91.074 |
| MD 337, deep GAB layer | 1st | 154.571 | 28.098 | 18.178 |
| MD 404 subgrade | 1st | 59.622 | 18.353 | 30.783 |
| MD 404 GAB | 1st | 60.762 | 12.977 | 21.357 |
| New York, embankment (local subgrade) | Lift 1, 1st | 38.377 | 6.049 | 15.763 |
| | Lift 2, 1st | 39.587 | 7.009 | 17.706 |
| Indiana, cement modified subgrade | 1st | 474.580 | 450.865 | 95.003 |
| Indiana, GAB | 1st | 203.105 | 173.983 | 85.661 |
| Missouri, GAB | 1st | 95.262 | 39.510 | 41.476 |
| | 2nd | 114.996 | 49.441 | 42.993 |
| Florida, Subgrade | 1st | 143.719 | 21.796 | 15.166 |
| Florida, Base | 1st | 127.102 | 34.888 | 27.449 |
| | 2nd | 157.572 | 22.020 | 13.975 |

## Appendix D- Results of LWD testing in the state of Maryland

The details for each tested project as well and measured LWD modulus and deflections in the field are presented in this section. The results are presented in English units due to MDOT SHA's requirements.

***Project: I-81 Widening and super structure (I-81 and MD 63)***

Contract number: WA3445272

**Date Visited:** 11/28/17

**Soil type:**

- 6" GAB placed on top of a foot of compacted silty clay with gravel and 4" crushed stone, silty clay subgrade

**Field Data Captured:**

- 16 spots of LWD testing every 25 feet on top of the freshly compacted GAB
- 16 spots of NDG testing (same spots as LWD testing locations) right after compaction
- Random GAB sampling for gravimetric moisture content oven testing in the lab, from top few inches of compacted material

**Notes:**

- Excessive water bleed from the GAB after compaction and retained on the surface of compacted layer which caused high deflection in some testing spots.

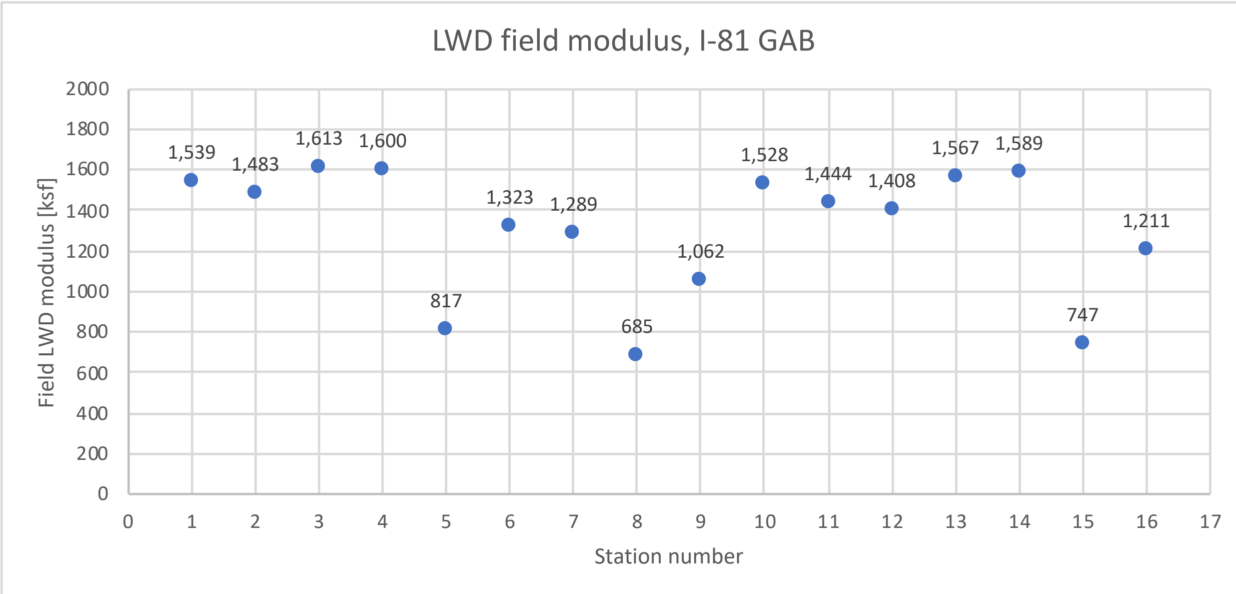



**Figure 115. LWD modulus measurements for I-81 project.**

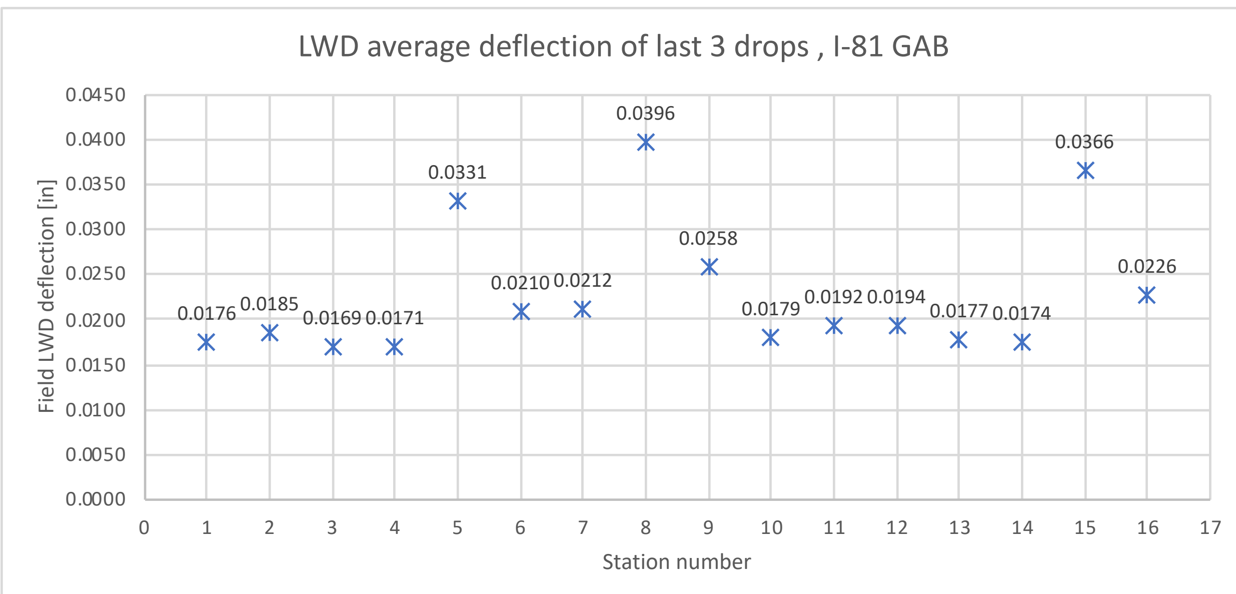



**Figure 116. LWD deflections measurements for I-81 project.**

***Project: Geometric improvement <u>MD 482 At Gorsuch road</u> and Cape Horn road***

Contract number: CL4515130

**Date Visited:** 10/19/17

**Soil type:** Common borrow material source: CJ Miller, Finksburge

**Field Data Captured:**

- 10 spots of LWD testing every 8 feet right after compaction
- 10 spots of NDG testing (same locations as LWD testing) right after compaction
- Random MC sampling for oven testing in the lab, from top few inches of soil layer

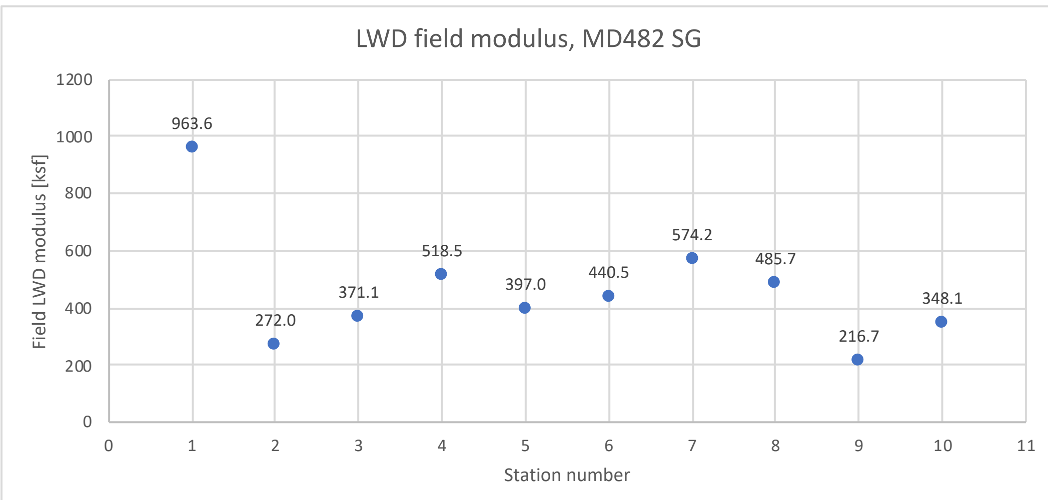



**Figure 117. LWD modulus measurements for MD482 project.**

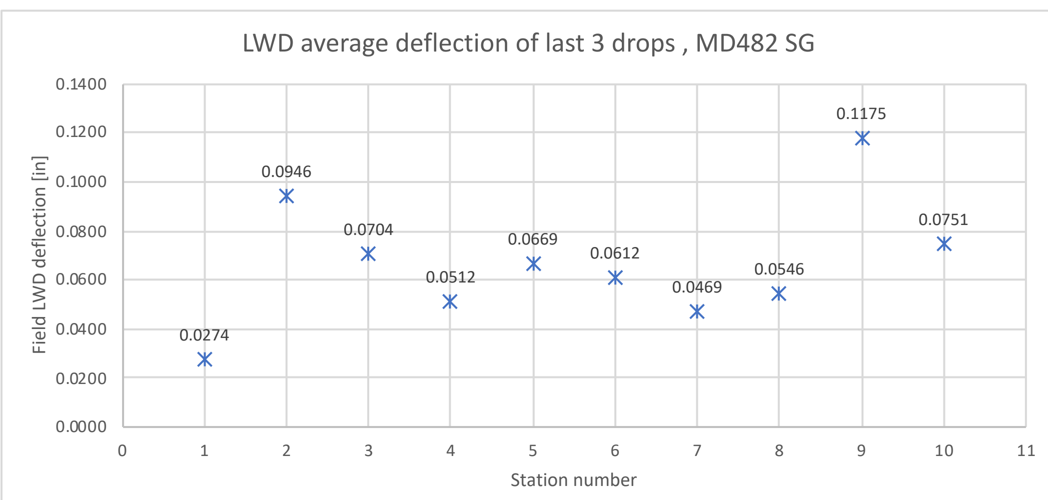



**Figure 118. LWD deflection measurements for MD482 project.**

***Project: Roundabout construction, MD 5 ramp at Brandywine road (MD 373/MD 381)***

Contract number: PG1755170

**Date Visited:** 10/18/17

**Soil type:**

- 5" GAB compacted on top of the dried and compacted embankment
- GAB source: Aggregate Industries Plant

**Field Data Captured:**

- 10 spots of LWD testing every 10 feet before GAB compaction on top of the embankment (SG)
- 10 NDG testing (same spots as LWD testing) before GAB compaction on the embankment
- 10 spots of LWD testing every 10 feet right after GAB compaction
- 3 NDG testing right after GAB compaction
- GAB was determined to be under compacted. More passes of vibratory roller compactor applied to reach higher PC (recompacted)
- 10 spots of LWD testing every 10 feet right after GAB recompaction
- 4 random NDG testing right after GAB recompaction
- Random MC sampling for oven testing in the lab, from top few inches of compacted GAB material

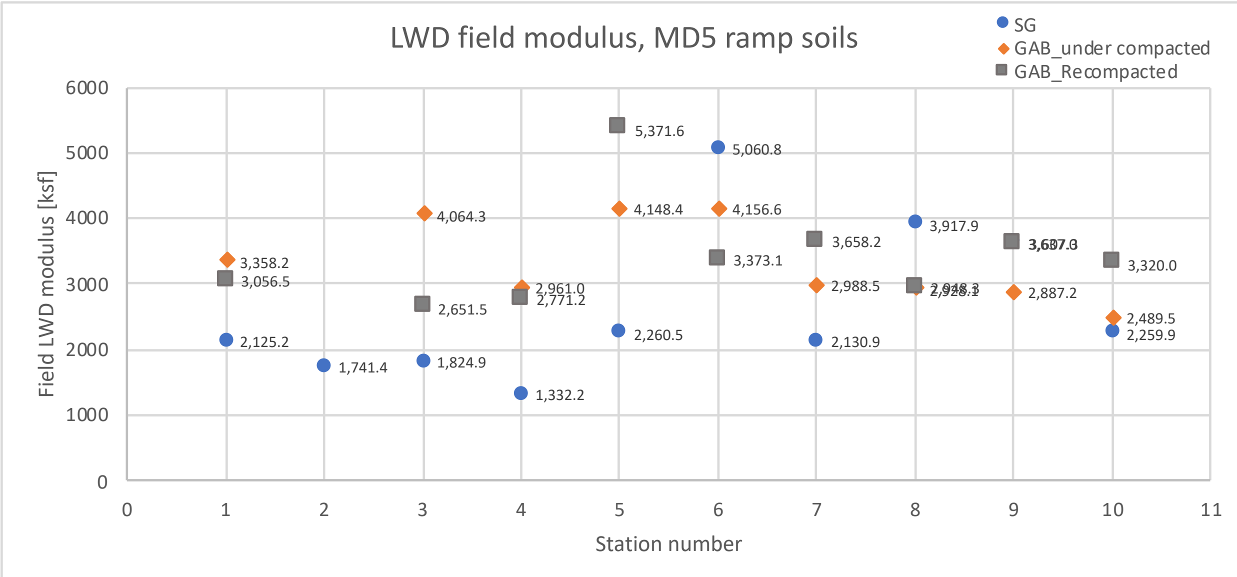


Figure 119. LWD modulus measurements for the MD5 ramp soils

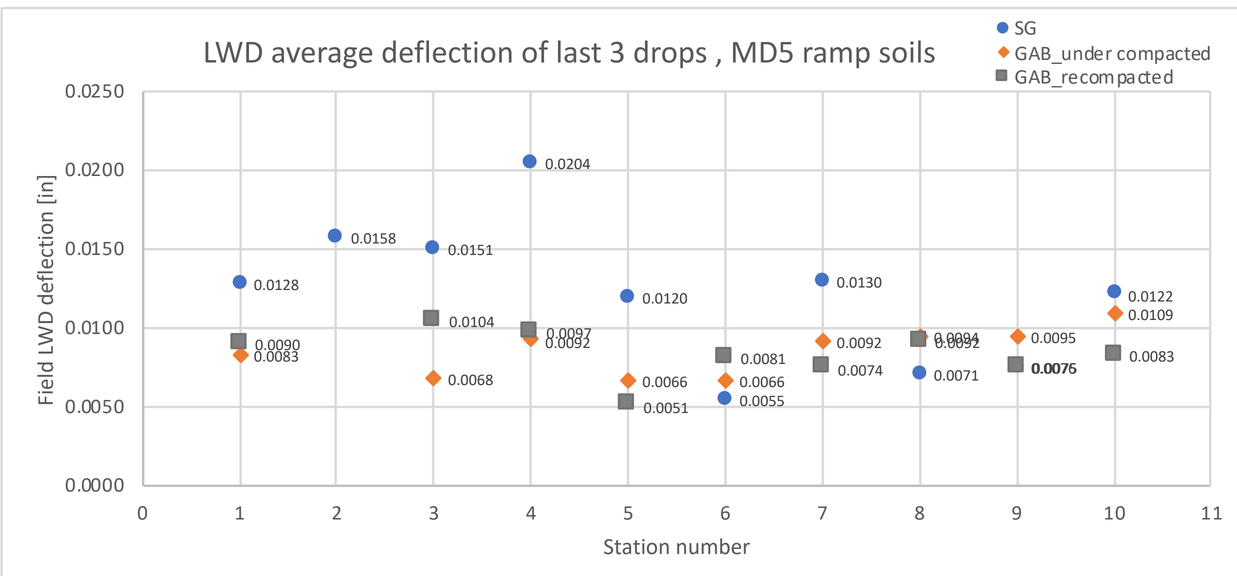


Figure 120. LWD deflection measurements for the MD5 ramp soils

***Project: Six Lane Reconstruction on MD175 from west of Reece road to east of Disney Road***

Contract number: AA4365471

**Dates Visited:** 10/23/2017, 10/25/2017

**Soil type:**

- Select borrow sand A-2-4 subgrade from Fort Meade stockpile A (testing locations 1 to 6) and A-1-b subgrade from East campus of FGGM (testing locations 6 to 15).
- Some soft clayey areas existed in the compacted subgrade with ~21% MC
- GAB source: Savage Stone, Laurel

**Field Data Captured:**

- 15 locations of LWD testing every 5 feet on the right land and left lane plus 8 LWD testing every 10 ft on the centerline of the road before GAB compaction on top of the SG
- 9 NDG testing before GAB compaction on the SG
- 15 locations of LWD testing every 5 feet on the right land and left lane plus 8 LWD testing every 10 ft on the centerline of the road right after GAB compaction
- 8 NDG testing right after GAB compaction
- GAB was determined to be under compacted. After two days, water was sprayed on the GAB with more passes of vibratory roller compactor to reach higher PC (recompacted)
- 15 locations of LWD testing every 5 feet on the right land and left lane plus 8 LWD testing every 10 ft on the centerline of the road right after GAB compaction
- 8 NDG testing right after GAB recompaction on some of the LWD testing locations
- Random MC sampling for oven testing in the lab, from top few inches of SG and GAB

- Soft spots on subgrade were observed and cut with a dozer. High expansive clayey spots were then sampled for further lab testing.

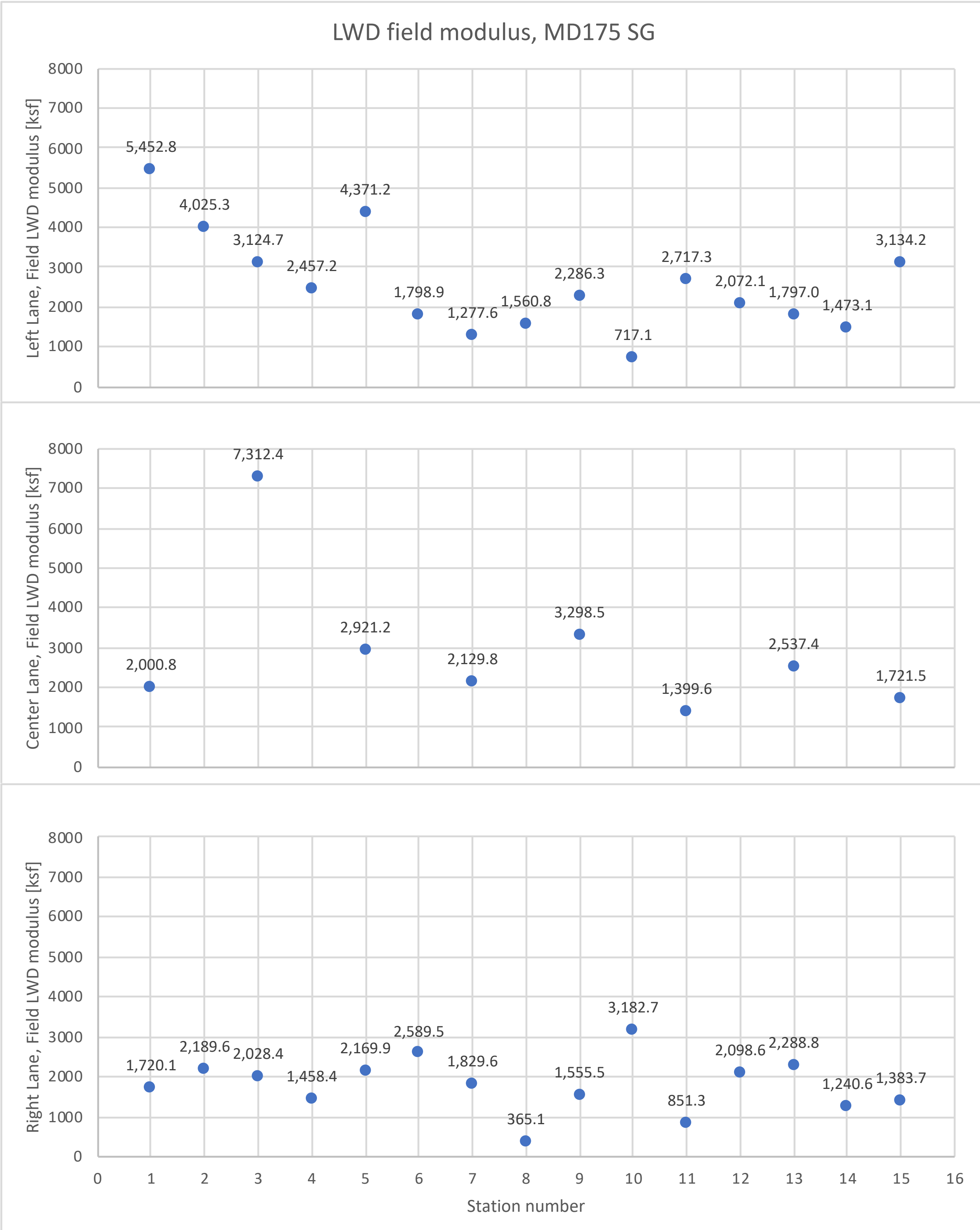



**Figure 121. LWD modulus measurements on MD175 SG.**

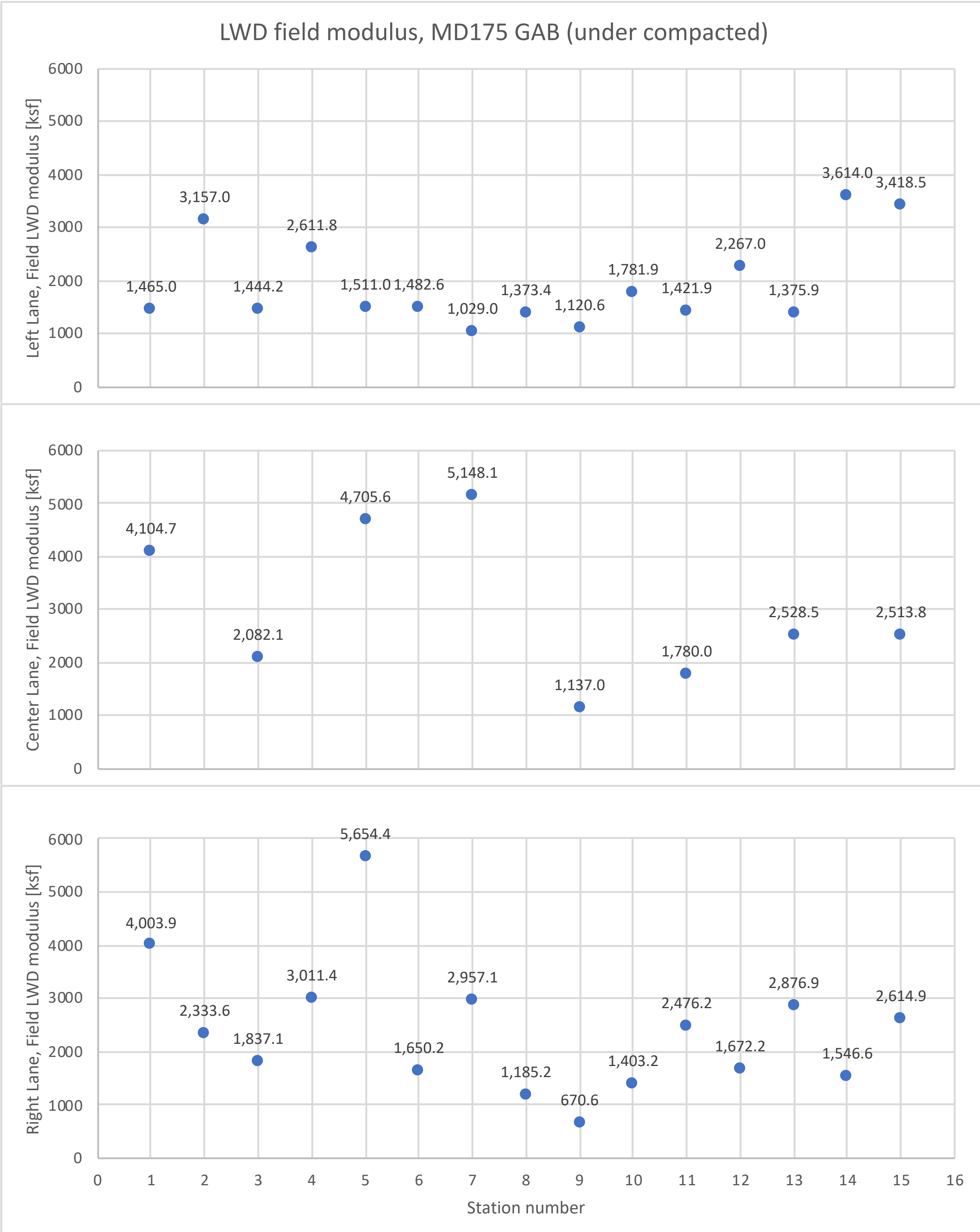


**Figure 122. LWD modulus measurements on MD175 under compacted GAB.**

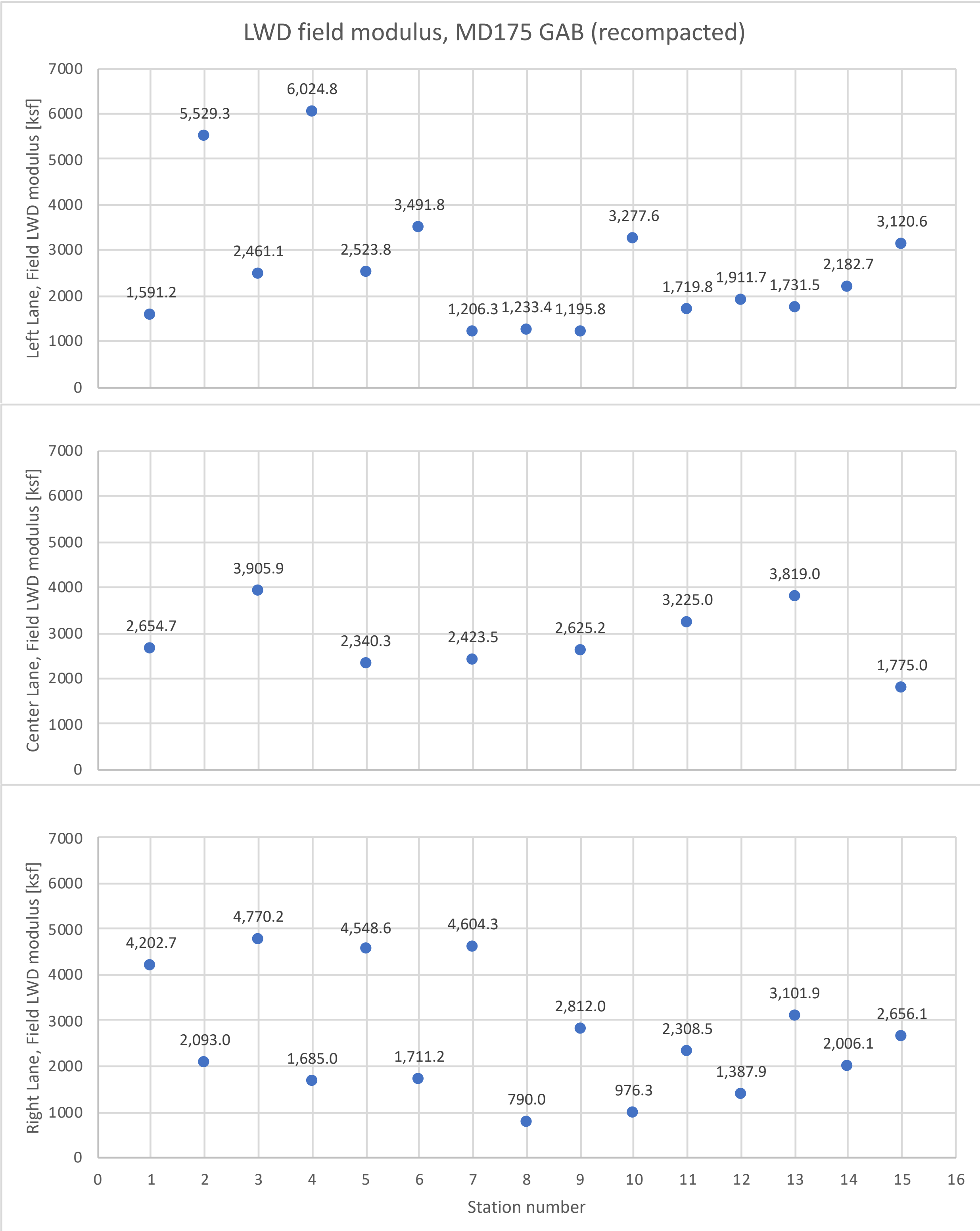



**Figure 123. LWD modulus measurements on MD175 recompacted GAB.**

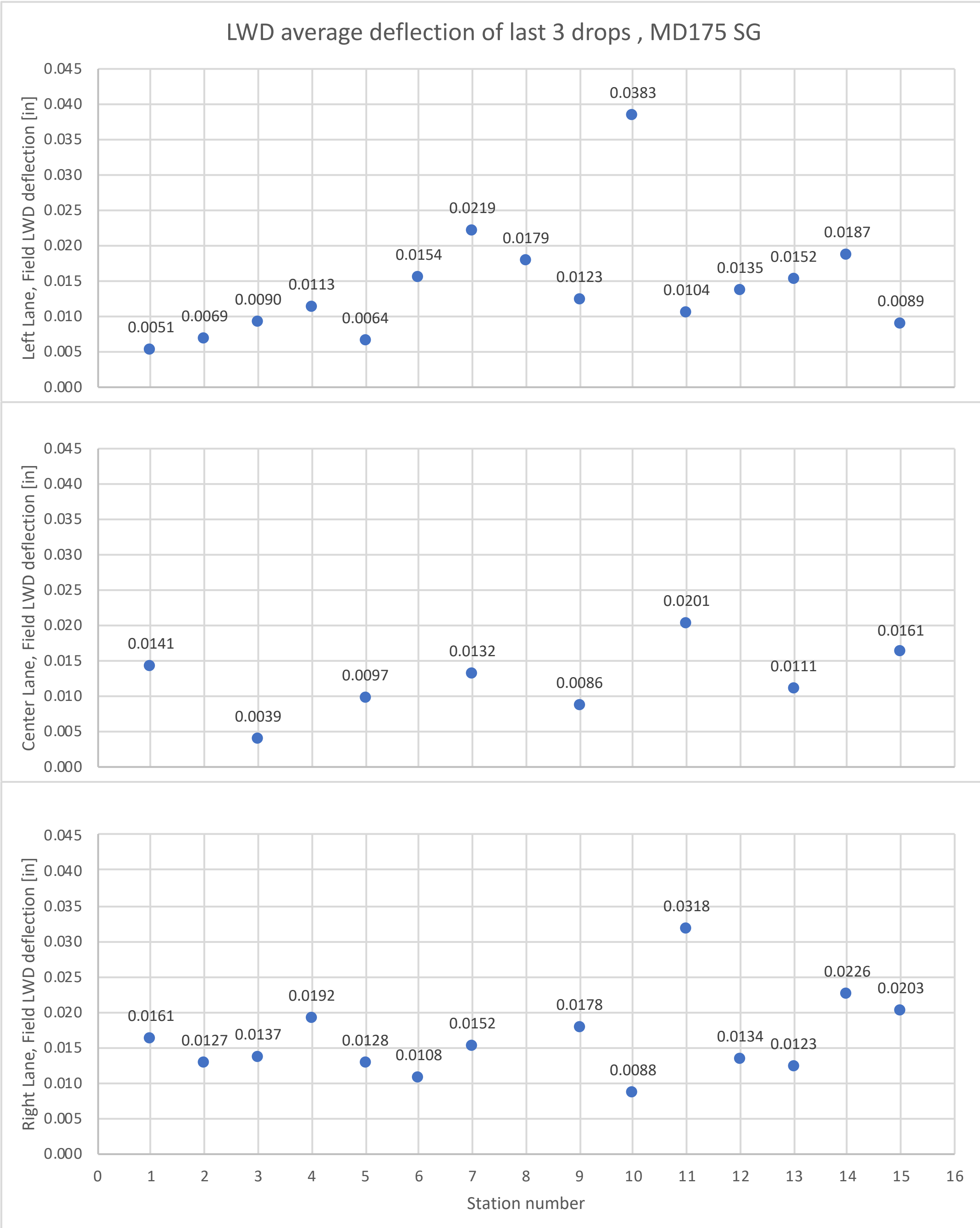



**Figure 124. Average last 3 drops LWD deflection on MD175 SG.**

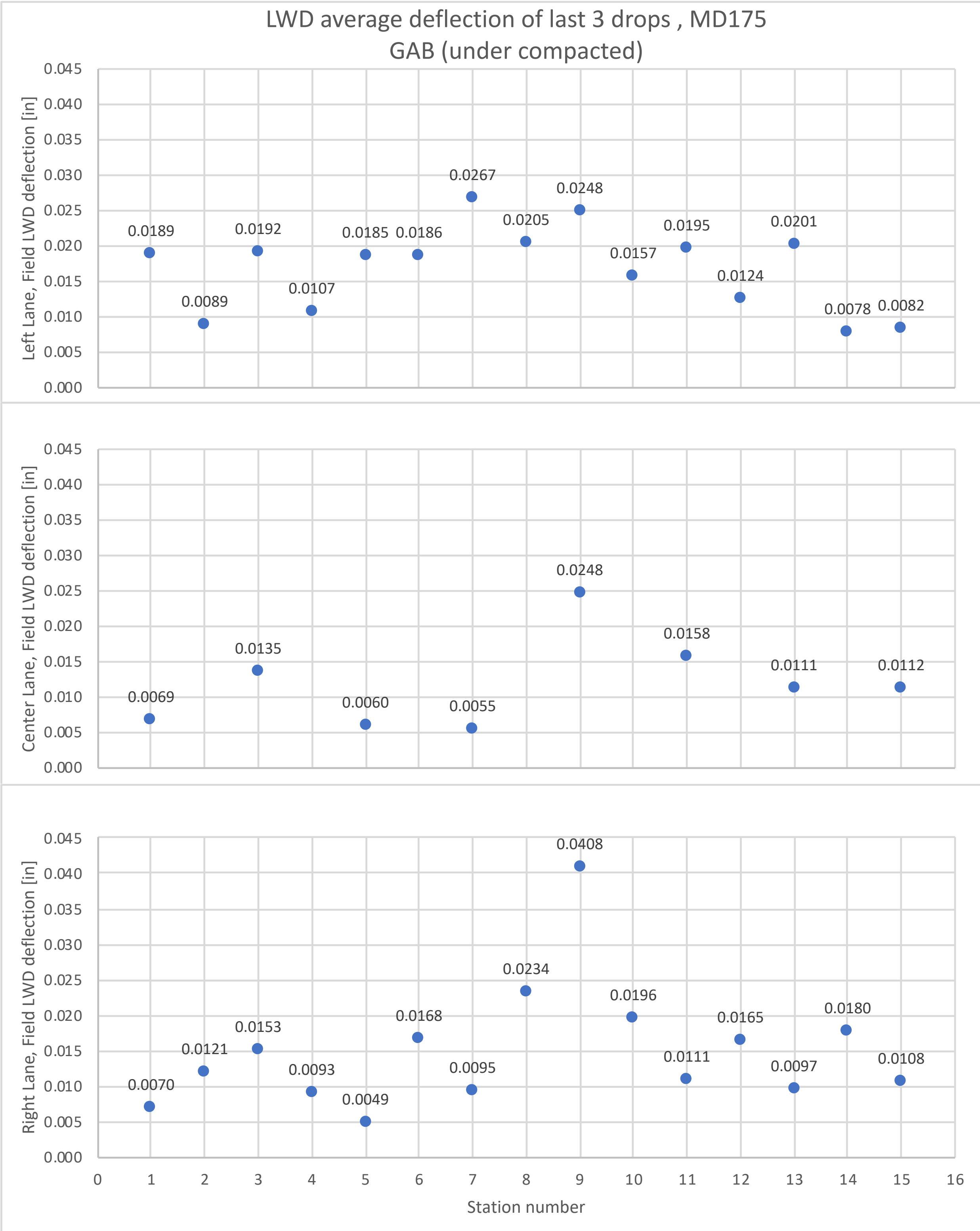



**Figure 125. Average last 3 drops LWD deflection on MD175 under compacted GAB.**

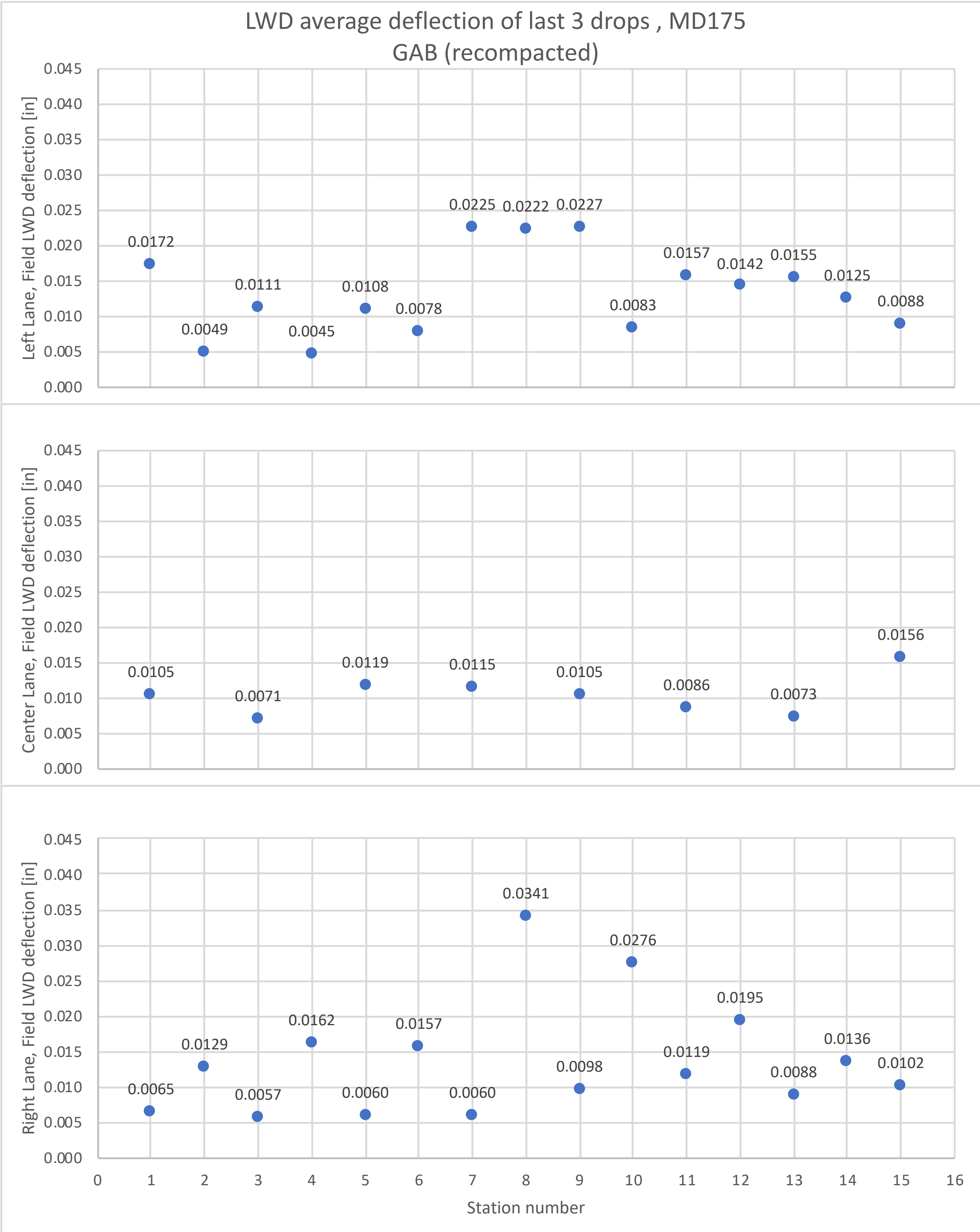



**Figure 126. Average last 3 drops LWD deflection on MD175 recompacted GAB.**

***Project: Replacement of Bridge on <u>MD355</u> in Fredrick County***

Contract number: FR5595180

**Soil type:**

- Temporary road to build new bridge over Monocacy river and fix the elevation to improve visibility
- 6" of common borrow shale placed on top of one foot of compacted common borrow soil
- The shale fill material included a great portion of rock, which were very large in dimensions

**Field Data Captured:**

- 10 stations of LWD, NDG, and Egauge testing every 10 feet on top of the fill material that were compacted a week before
- 8 stations of LWD testing every 5 feet on top of a freshly compacted fill section and two stations of NDG testing.
- Compacted fill material sampled (compacted last week section) for MC oven testing in the lab (Figure 127).
    - UMD samples were taken from top 3", and MDOT SHA samples from 6" below the surface for oven drying.
    - NDG measurements were taken at 6" depth.
    - Egauge 1 MC measurements were conducted inserting the probe to the same hole as NDG, but Egauge 2 in a new spot adjacent to the NDG's hole.

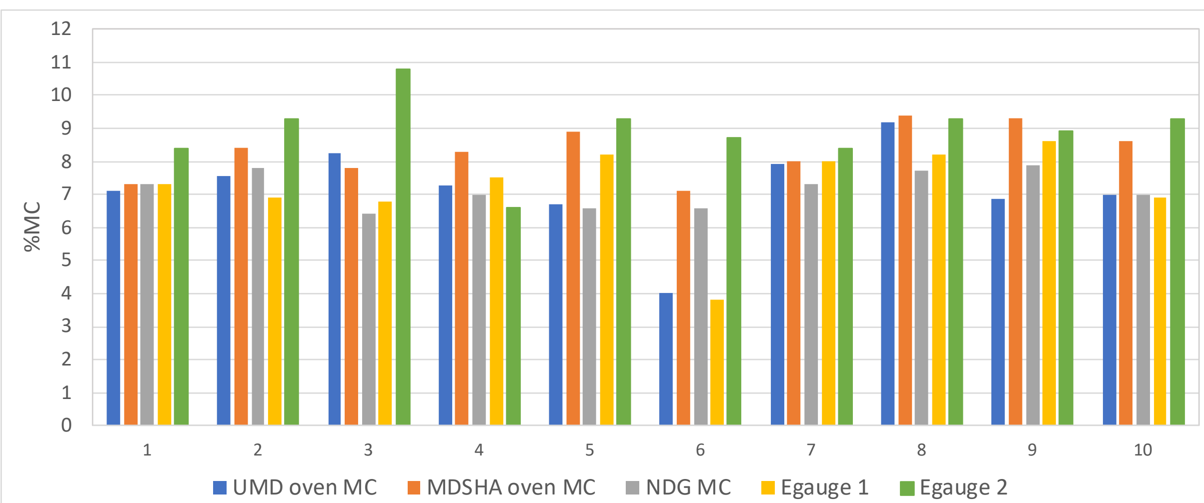



**Figure 127. Percent MC comparison for NDG, Egauge, and MC samples taken by UMD and MDOT SHA.**

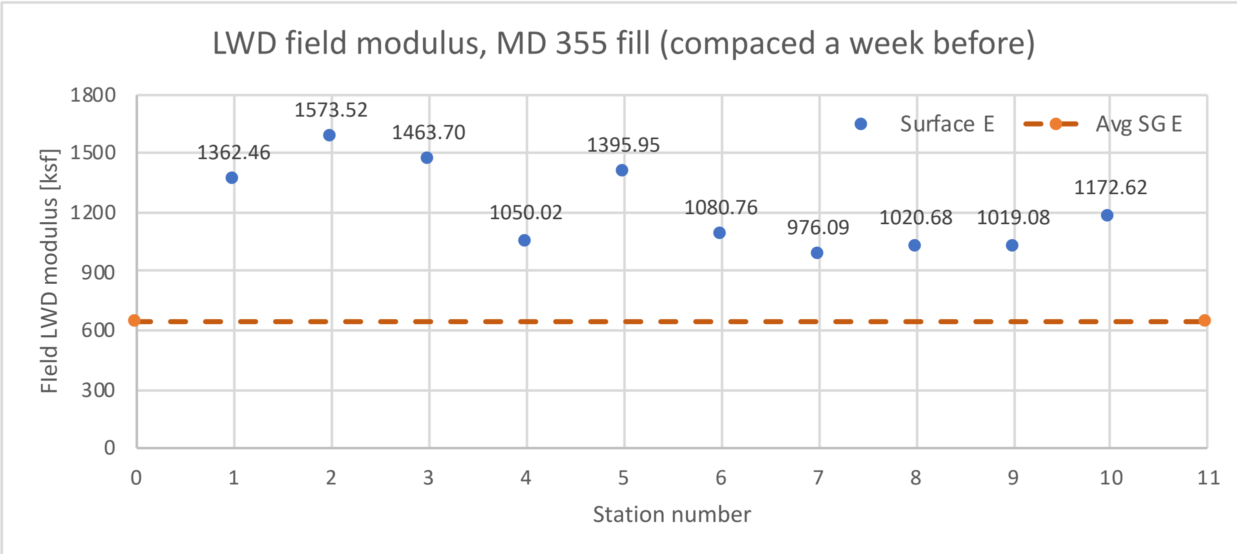



**Figure 128. LWD field modulus for MD355 fill material compacted a week before testing.**

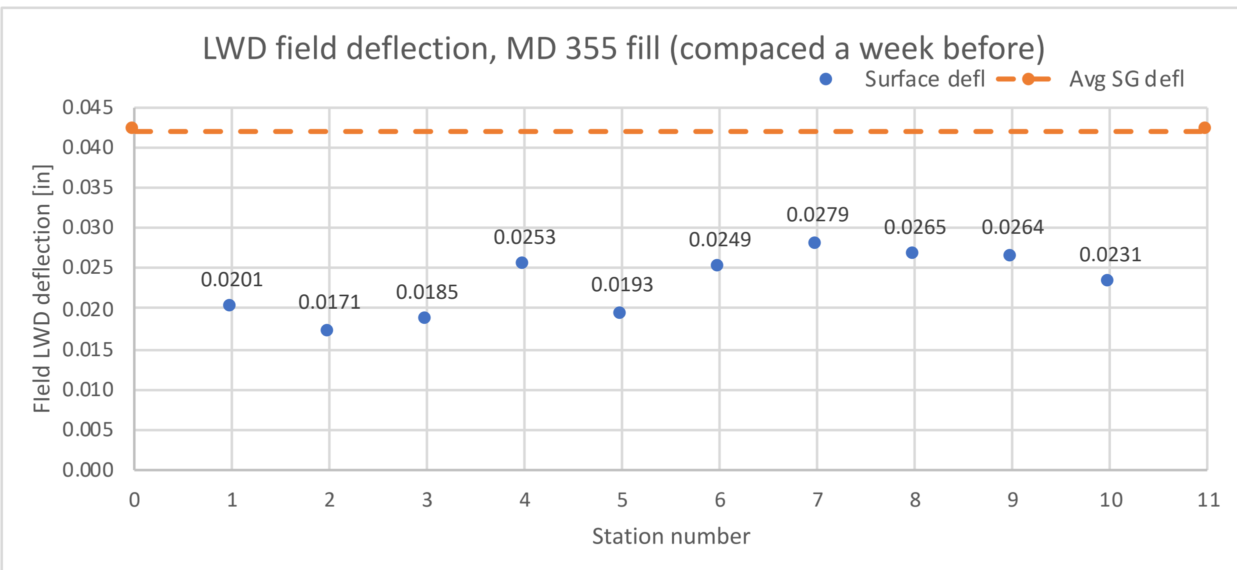



**Figure 129. LWD field deflection for MD355 fill material compacted a week before testing.**

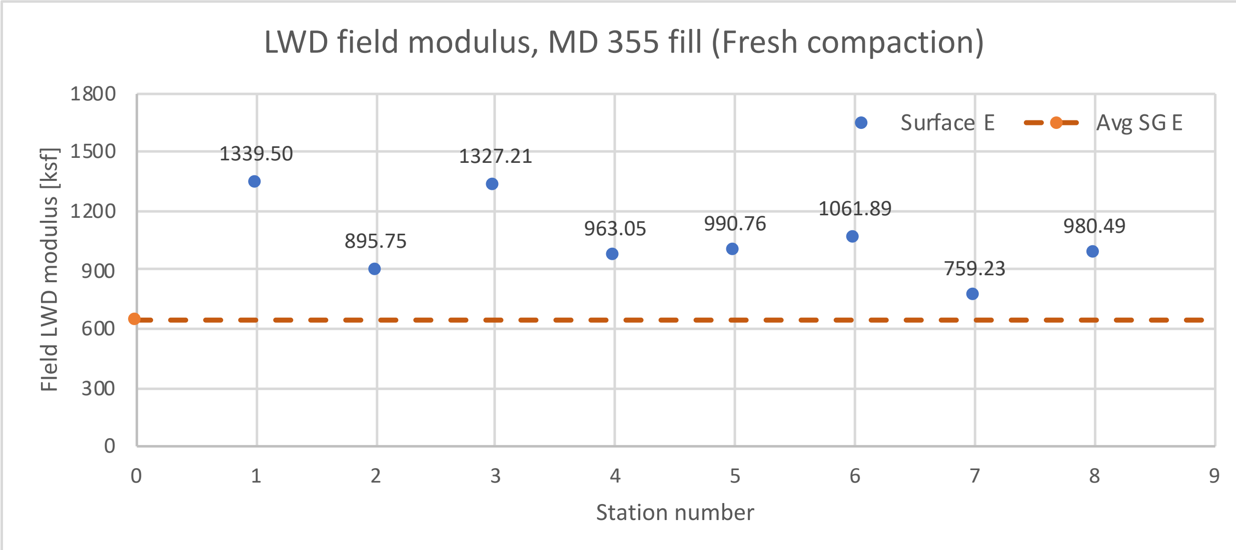


**Figure 130. LWD field modulus for MD355 fill section right after compaction.**

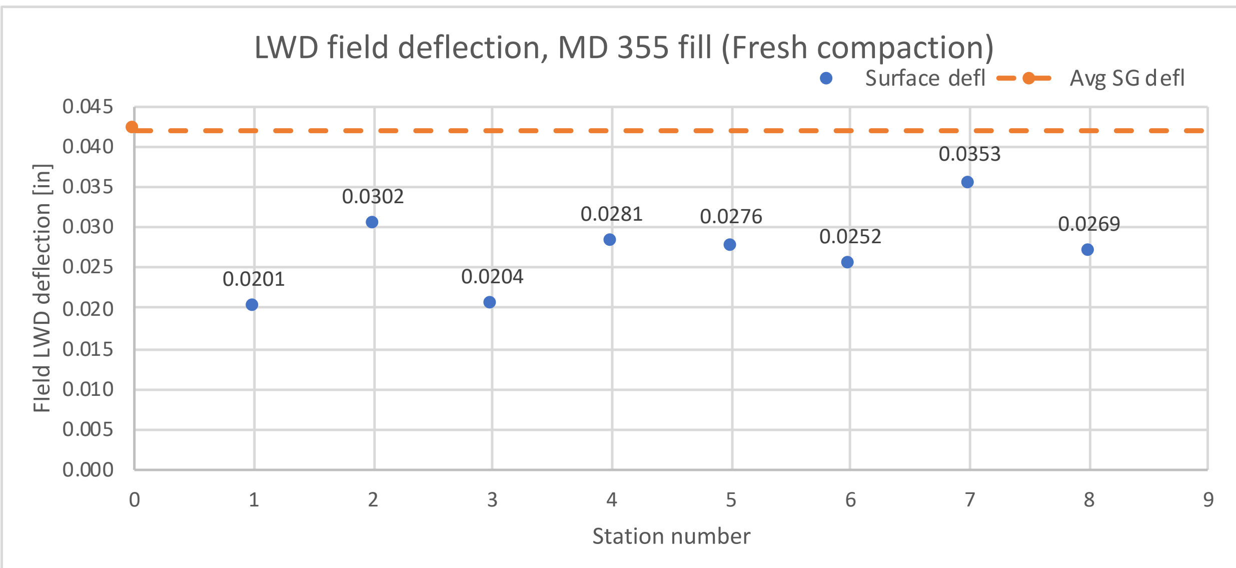


**Figure 131. LWD field deflection for MD355 fill section right after compaction.**

***Project: Multi lane construction on <u>I-695</u> from MD 144 to south of US 40***

Contract number: BA7275172- Road extension and curb construction

**Soil type:**

- Two layers of 6" deep (12" total) GAB from Martin Marietta Materials's Texas quarry compacted (using sheep foot roller compactor!) on top of the subgrade the day before testing.

**Field Data Captured:**

- 10 spots of LWD, NDG, and Egauge testing every 10 feet on top of the GAB material.
- 3 spots of random LWD testing on top of the subgrade.
- GAB material sampled for MC oven testing in the lab (Figure 132).
    - UMD samples were taken from top 3", and MDOT SHA samples from 6" below the surface for oven drying.
    - NDG measurements were taken at 6" depth.
    - Egauge MC measurements were conducted in a new spot adjacent to the NDG's hole.

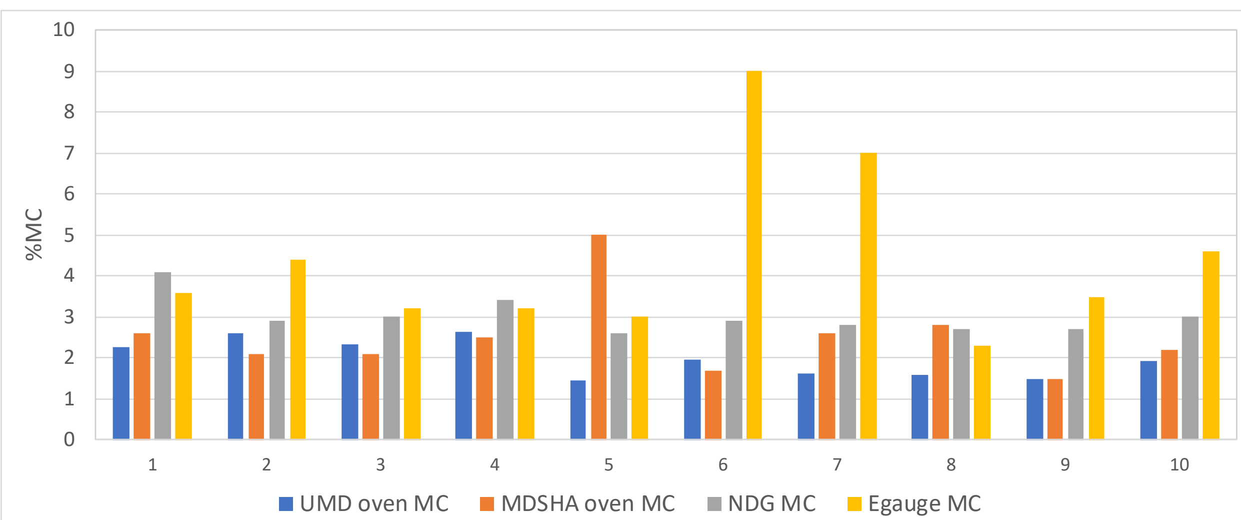



**Figure 132. Percent MC comparison for NDG, Egauge, and MC samples taken by UMD and MDOT SHA.**

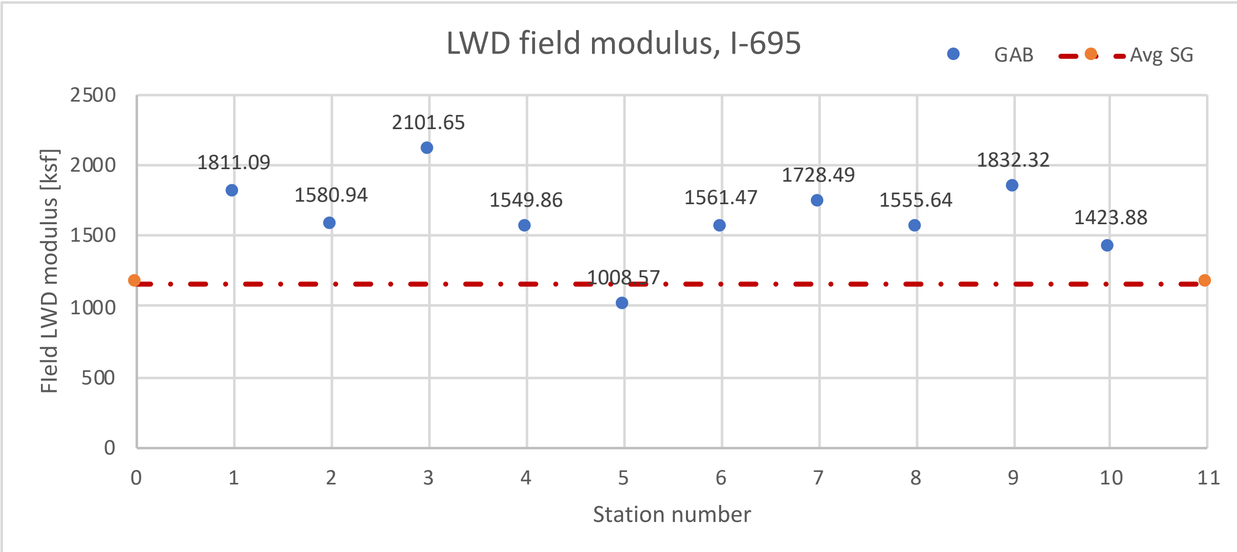



**Figure 133. LWD field modulus forI-695 GAB and subgrade.**

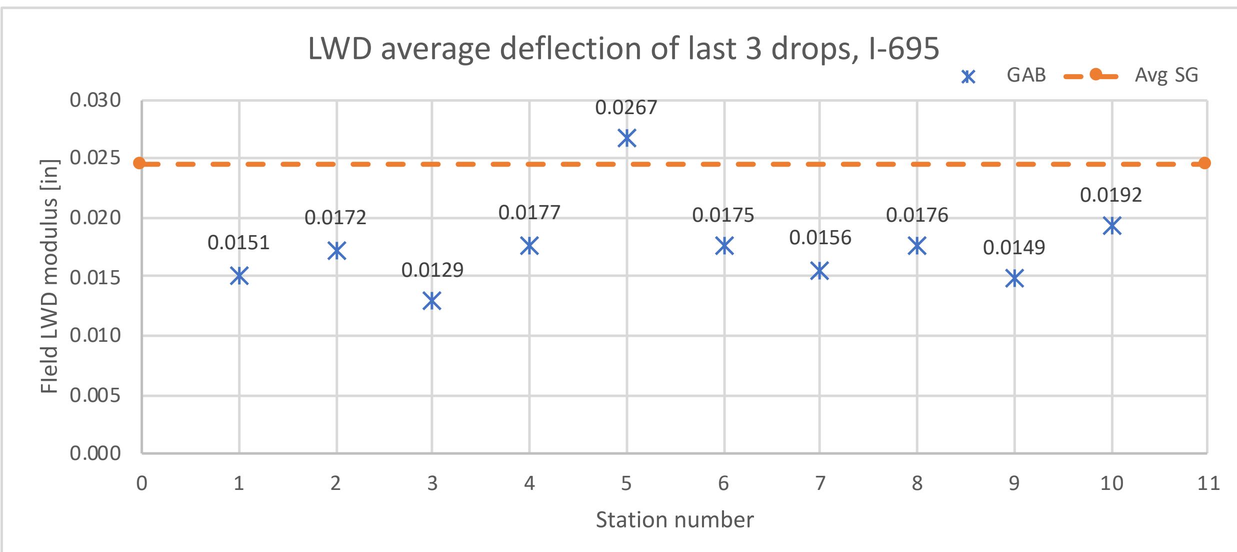



**Figure 134. LWD field deflection forI-695 GAB and subgrade.**

***Project: <u>I 270</u> at Watkins Mill road, MD 124 to Great Seneca Creed crossing- Interchange construction***

Contract number: MO355172R

**Soil type:**

- Common borrow fill material compacted 3 weeks before testing, the water truck sprayed water a few times for dust control during the 3 weeks.

**Field Data Captured:**

- 10 spots of LWD testing every 10 feet on top of the fill material.
- 12 spots of NDG, and Egauge (at 6" deep), testing in the 10 feet grid.
- Fill material sampled for MC oven testing in the lab (Figure 135).
    - UMD samples were taken from top 3", and MDOT SHA samples from 6" below the surface for oven drying.
    - NDG measurements were taken at 6" depth.
    - Egauge MC measurements were conducted in a new spot adjacent to the NDG's hole.
    - Egauge 1 MC measurements were conducted inserting the probe to the same hole as NDG, but Egauge 2 in a new spot adjacent to the NDG's hole (6" deep).

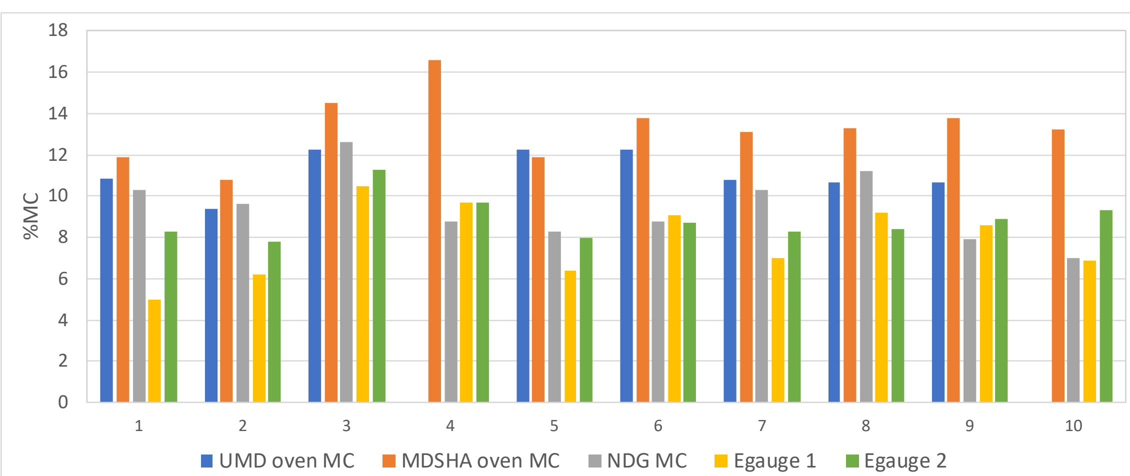


**Figure 135. Percent MC comparison for NDG, Egauge, and MC samples taken by UMD and MDOT SHA (I-270 fill).**

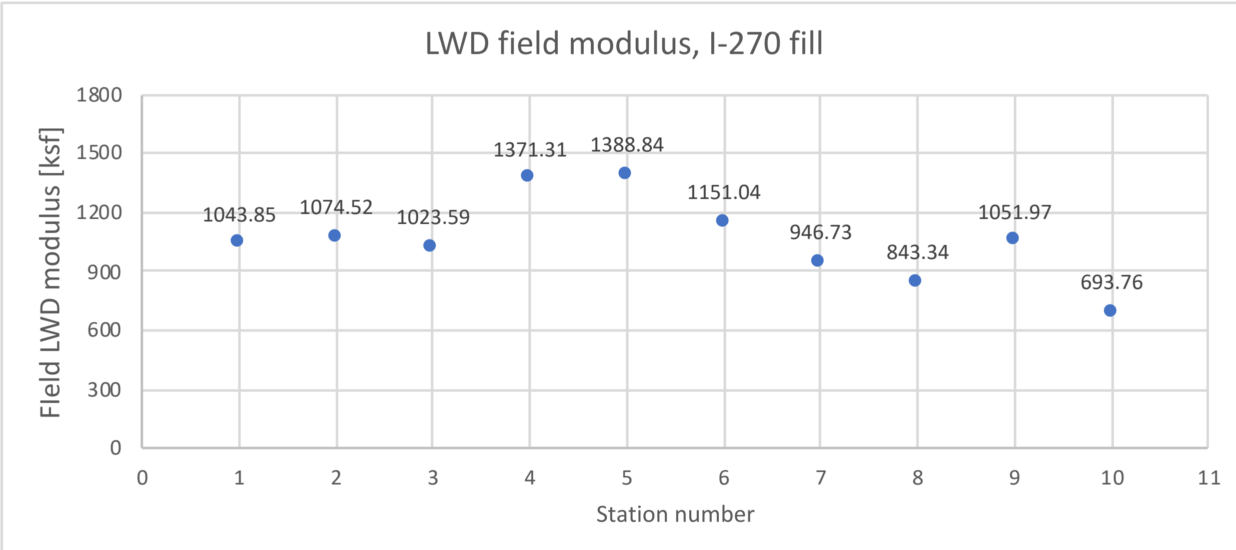



**Figure 136. LWD field modulus for I-270 fill compaction.**

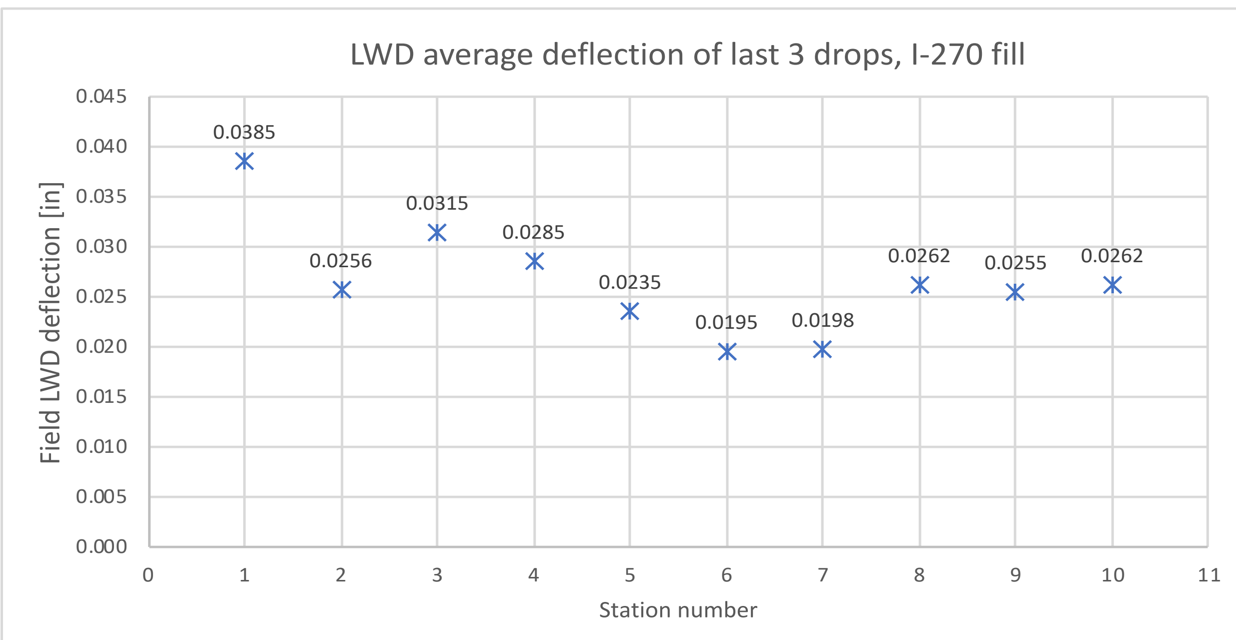



**Figure 137. LWD field deflections for I-270 fill compaction.**

***Project: MD 32 widening from MD 108 to Linden Church Road***

Contract number: HO1415170

**Soil type:**

- Tested right after compaction of 6” GAB at base layer elevation, on top of a SG, overlain by a geotextile, 12” GAB, an extra 2” GAB for grading (14” GAB total below the tested layer).

**Field Data Captured:**

- Round 1 of testing on 06/05/2018 (R1):
    - 12 spots of LWD (300 mm plate) testing every 10 feet on top of the GAB layer.
    - 12 spots of LWD (200 mm plate) testing every 10 feet on top of the GAB layer.
    - 12 spots of LWD (300 mm plate, without the plugin) testing every 10 feet on top of the GAB layer.
    - 12 stations of NDG, and 10 stations of Egauge (at 6” deep), testing 10 feet apart.
    - Ohaus MC analyzer used to determine the MC at the time of compaction: <u>4.05%</u> (@120C and 7min duration)
- Round 2 of testing on 06/06/2018, 10 AM (R2):
    - 10 spots of LWD (300 mm plate) testing every 10 feet on top of the GAB base layer.
    - 10 spots of LWD (300 mm plate, without the plug in) testing every 10 feet on top of the GAB layer.
    - 10 spots of LWD (200 mm plate) testing every 10 feet on top of the GAB layer.
    - 10 spots of NDG testing 10 feet apart.
- Round 3 of testing on 06/06/2018, 11:30 AM (R3):

- In an attempt to test on a compacted section with all NDG tested spots above 97 PC, the testing strip was reworked by few more passes of the roller compactor.
- Repeated LWD testing 10 spots (300 mm plate) testing every 10 feet on top of the GAB layer. Repeated NDG for the failing spots only (5 stations).

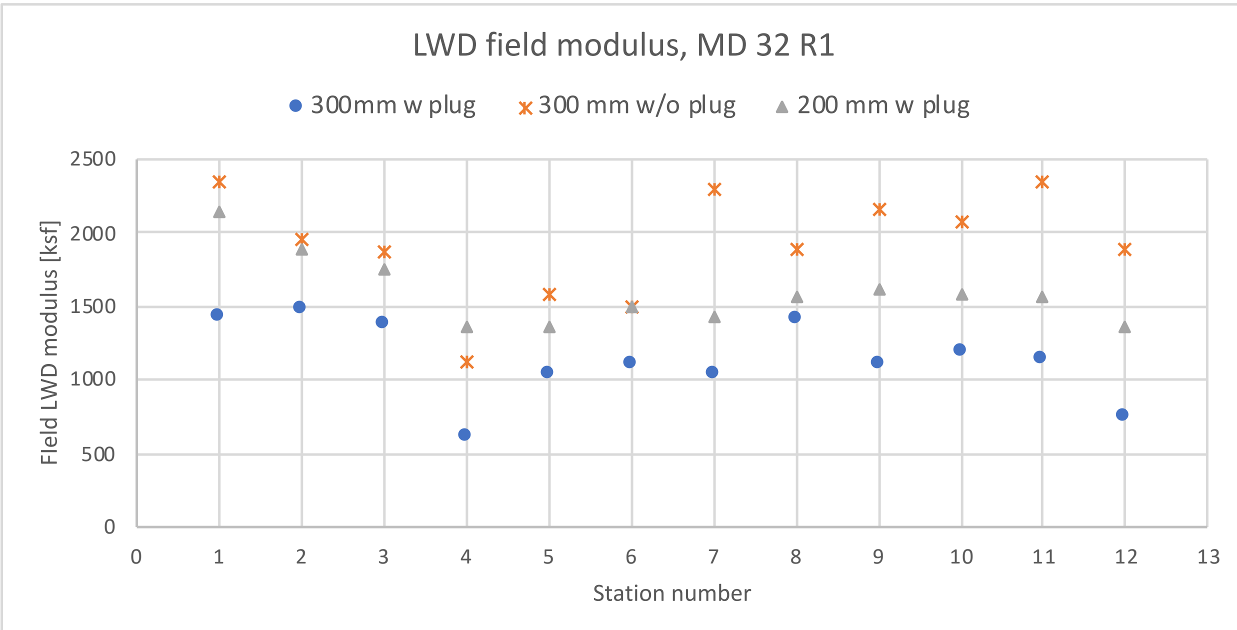



**Figure 138. LWD field modulus with different plate and sensor configuration for MD32, Round1.**

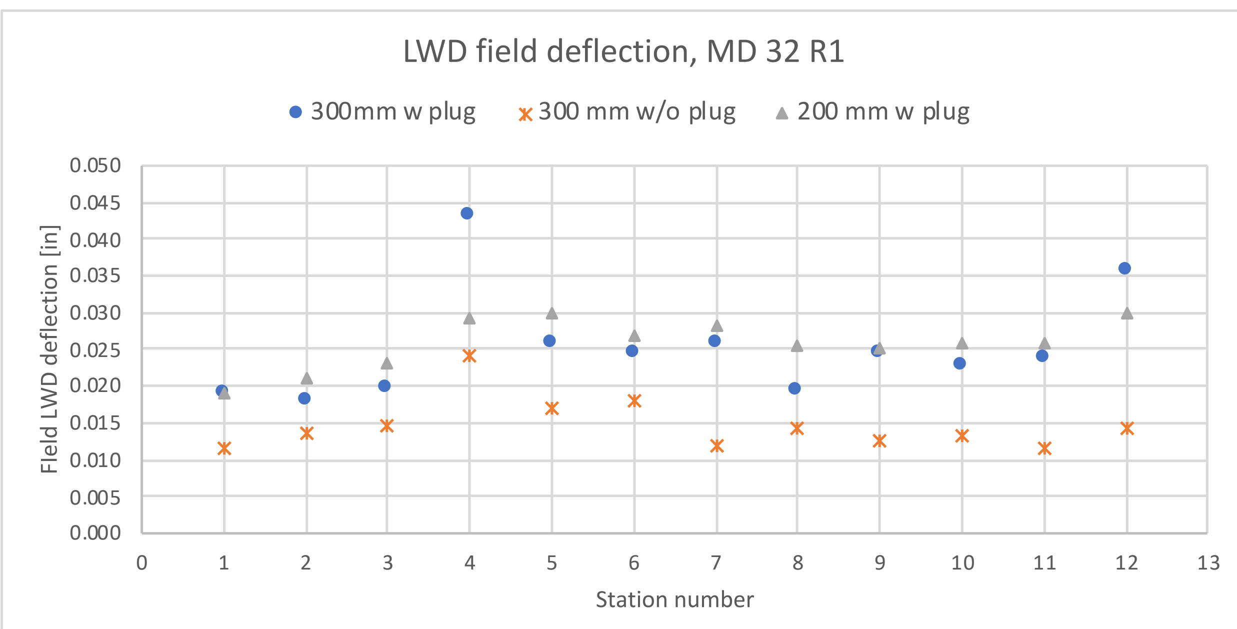



**Figure 139. LWD field deflections with different plate and sensor configuration for MD32, Round1.**

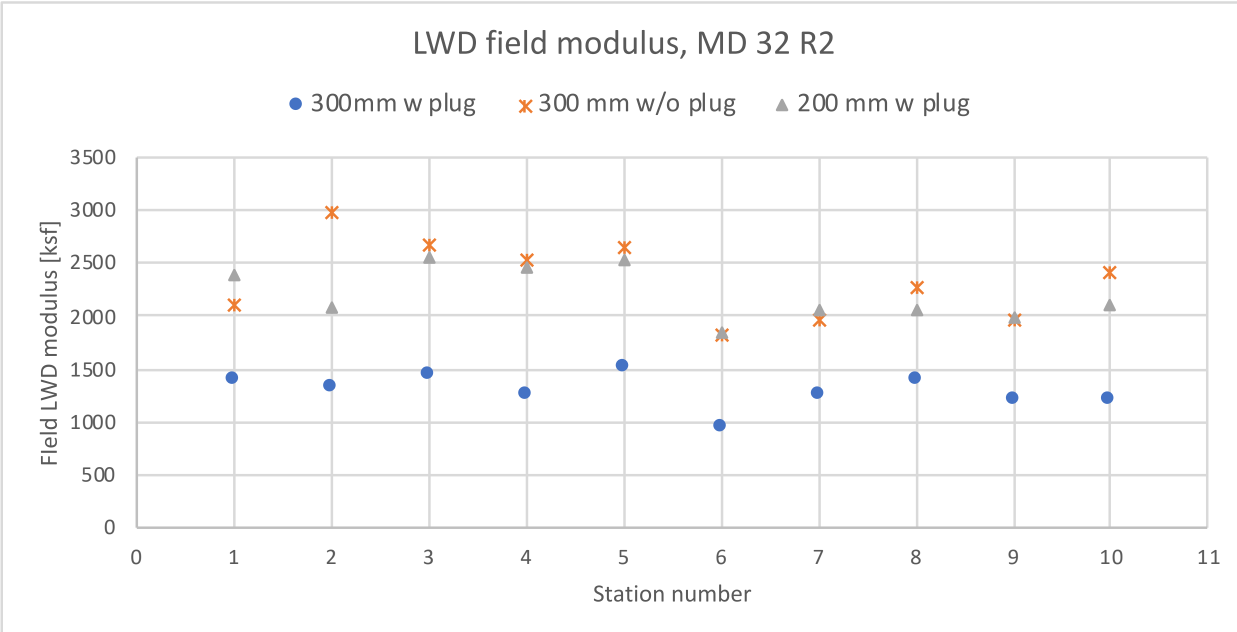



**Figure 140. LWD field modulus with different plate and sensor configuration for MD32, Round2.**

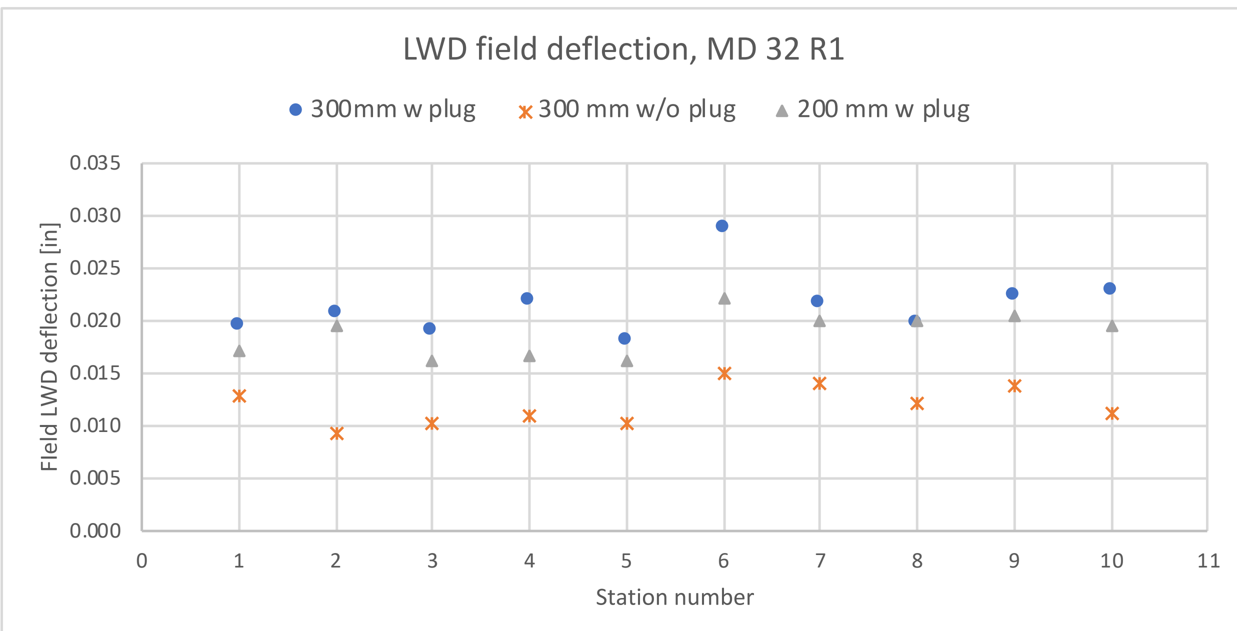



**Figure 141. LWD field deflection with different plate and sensor configuration for MD32, Round2.**

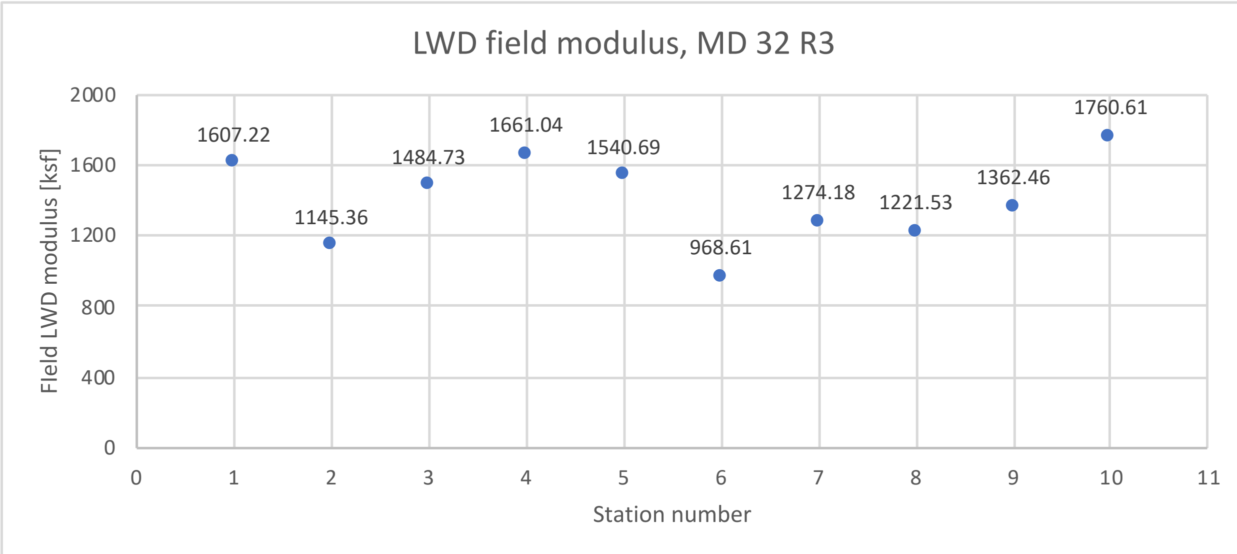



**Figure 142. LWD field modulus forMD32, Round 3.**

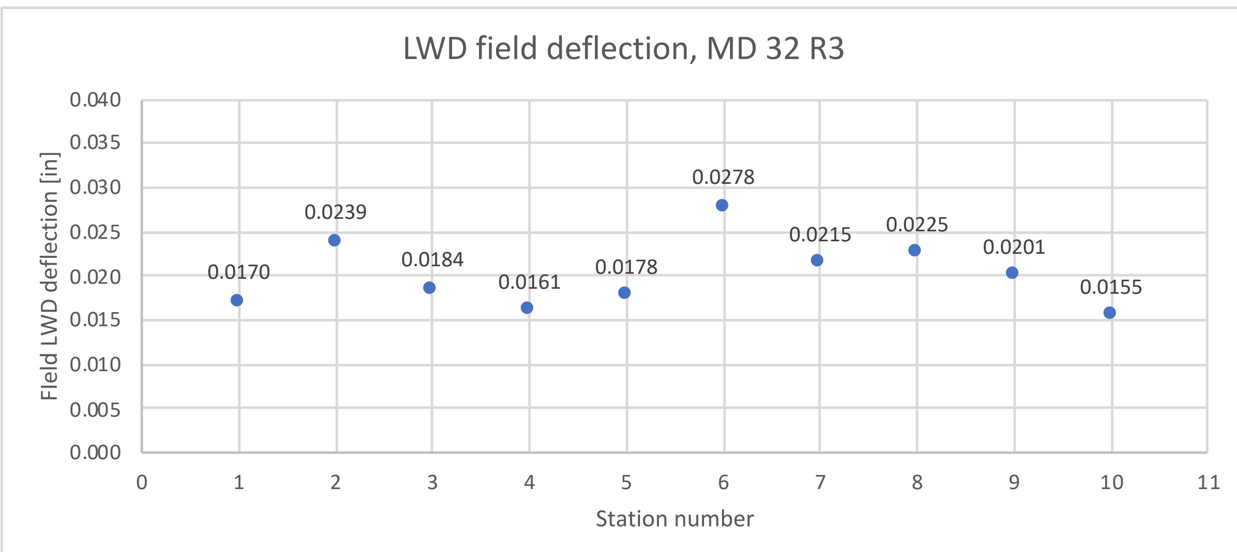



**Figure 143. LWD field deflection forMD32, Round 3.**

**Figure 144. GAB spreading and compacting, bulk sampling from the GAB stockpile, Dynatest LWD testing (300 and 200 mm diameter plates), Egauge and NDG testing, Ohaus Moisture Analyzer in action.**

***Project: Interchange construction, MD 5 Interchange at Brandywine road (MD 373/MD 381)***

Contract number: PG1755170

**Soil type:**

- Tested a day after compaction of two layers of 5” GAB compacted over an undercut and fill with bankrun gravel (naturally graded gravel).

**Field Data Captured:**

- 10 spots of LWD (300 mm plate) testing 10 feet apart on the GAB layer.
- 10 spots of LWD (200 mm plate) testing 10 feet apart on the GAB layer.
- 10 spots of NDG (direct transmission mode at 4” deep), and 10 stations of Egauge (at 6” deep), testing 10 feet apart.
- Ohaus MC analyzer to determine MC at the time of testing on 6 locations, 120C temperature and maximum 10 minutes drying duration (Figure 145):
    - Samples for Ohaus analyzer were obtained from top 3”, and MDOT SHA samples from 4” below the surface for oven drying.
    - NDG measurements were taken at 4” depth.
    - Egauge 1 MC measurements were conducted inserting the probe to the same hole as NDG, but Egauge 2 in a new spot adjacent to the NDG’s hole (6” deep).

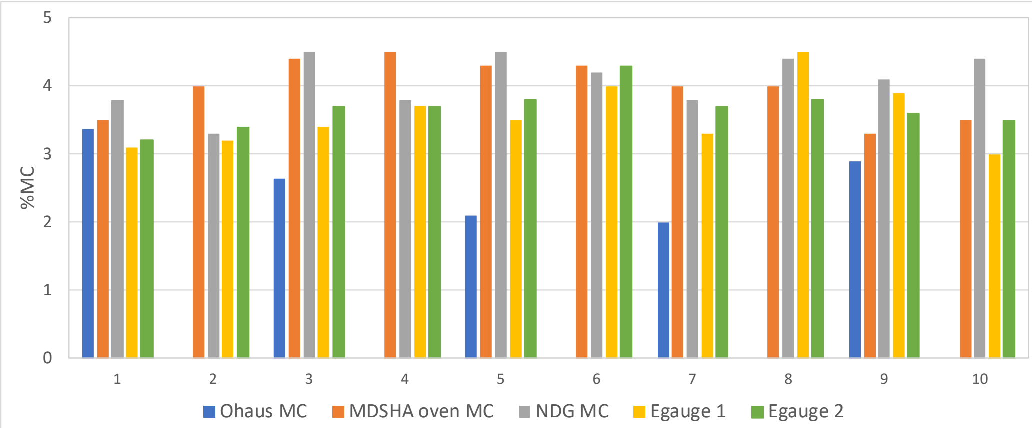



**Figure 145. Percent MC comparison for NDG, Egauge, and Ohaus moisture analyzer (MD5 Interchange)**

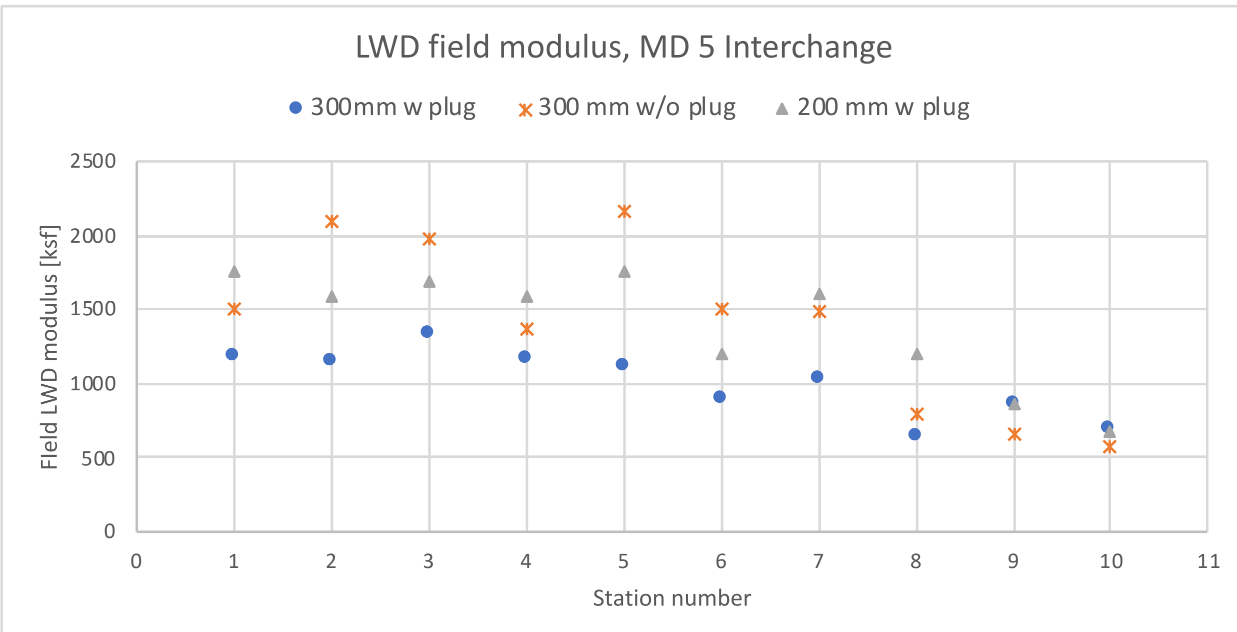



**Figure 146. LWD field modulus with different plate sizes and sensor configuration for MD5 interchange construction.**

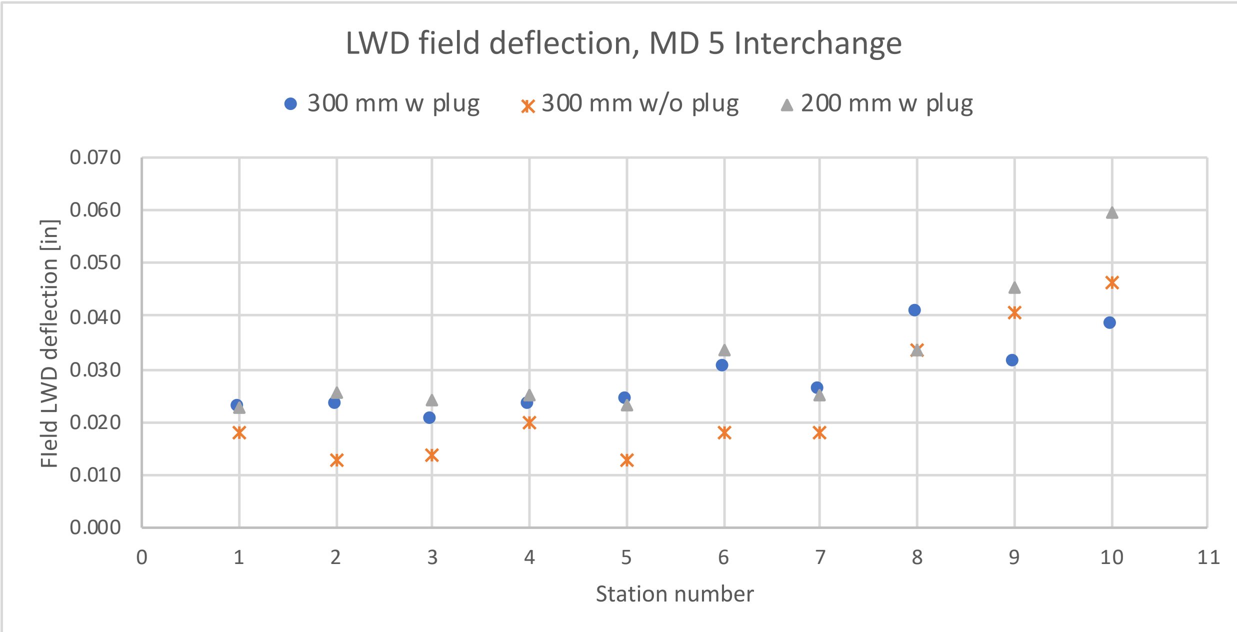



**Figure 147. LWD field deflections with different plate sizes and sensor configuration for MD5 interchange construction.**

***Project: <u>I 95 Bridge</u> (#1616205) replacement over Suitland road- Bridge***

Contract number: PG6985180

**Soil type:**

- Tested on top of the crushed run aggregate fill (CR-6 stone) at median bridge abutment, 6 layers of 6", total 36".
- Tested a few spots on top of the GAB compacted on top of the fill (GAB from Aggregate Industries, Rockville Quarry)
- Since the %MC of the fill material was high, removing and replacing the last layer was recommended.

**Field Data Captured:**

- 8 spots of LWD testing 8 feet apart on the fill.
- 3 spots of LWD testing 10 feet apart on the GAB layer.
- 7 spots of NDG (direct transmission mode at 6" deep) same locations as LWD testing.
- Ohaus moisture analyzer to determine MC at the time of testing on the fill at 120C temperature: <u>4.01%.</u>

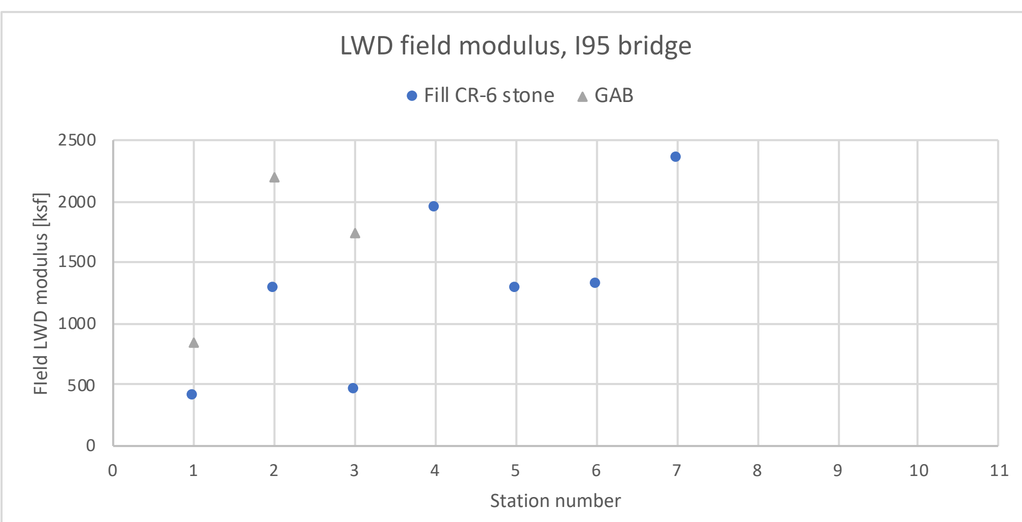



**Figure 148. LWD field modulus for I-95 bridge abutment construction.**

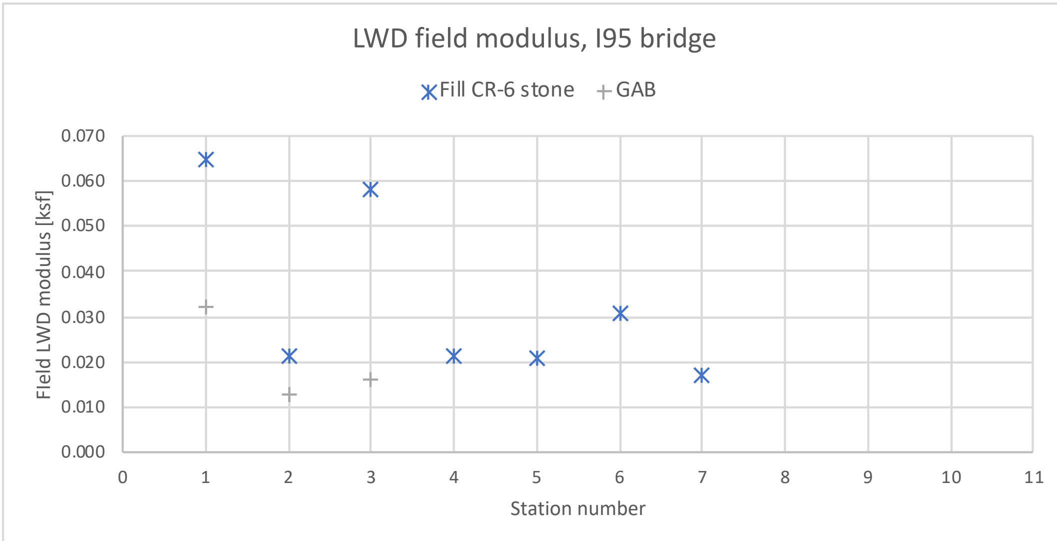


Figure 149. LWD field deflections for I-95 bridge abutment construction.

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